AD-A058 529 ROCKWELL INTERNATIONAL LOS ANGELES CA LOS ANGELES DIV F/G 11/4
NEW CONCEPTS IN COMPOSITE MATERIAL LANDING GEAR FOR MILITARY AI--ETC(U)
FEB 78 V E WILSON F33615-76-C-3021
UNCLASSIFIED AFFDL-TR-78-2-VOL-1 NL

1 OF 2
AD
A058529

AFFDL-TR-78-2
VOLUME I

NEW CONCEPTS IN COMPOSITE MATERIAL LANDING GEAR FOR MILITARY AIRCRAFT
TECHNICAL DISCUSSION
VOLUME I

ROCKWELL INTERNATIONAL CORPORATION, LOS ANGELES DIVISION
LOS ANGELES, CALIFORNIA

FEBRUARY 1978

TECHNICAL REPORT AFFDL-TR-78-2, VOLUME I

FINAL REPORT FOR PERIOD APRIL 1976 - FEBRUARY 1978

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT-AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

James R. Hampton

JAMES R. HAMPTON
Project Engineer
Mechanical Branch

Howell K. Brewer

HOWELL K. BREWER, Chief
Mechanical Branch
Vehicle Equipment Division
AF Flight Dynamics Laboratory

FOR THE COMMANDER

Ambrose B. Nutt

AMBROSE B. NUTT, Director
Vehicle Equipment Division
AF Flight Dynamics Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFFDL/FEM *,W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/21 August 1978 — 300

19 TR-78-2-VOL-1

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 18 AFFDL-TR-78-2, Volume I

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle) 6 NEW CONCEPTS IN COMPOSITE MATERIAL LANDING GEAR FOR MILITARY AIRCRAFT. VOLUME I. TECHNICAL DISCUSSION.

5. TYPE OF REPORT & PERIOD COVERED 9 FINAL RE[redacted]T. Apr[redacted]976 - Feb[redacted]978.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s) 10 V. E. WILSON

8. CONTRACT OR GRANT NUMBER(s) 15 F33615-76-C-3021 new

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Rockwell International Corp.
Los Angeles Division
5701 W. Imperial Highway
Los Angeles, Ca. 90009

16 2402

17 Ø1

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
PE 62201F
WU AFFDL-2402-01-14

11. CONTROLLING OFFICE NAME AND ADDRESS
Air Force Flight Dynamics Laboratory (FEM)
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

12. REPORT DATE 11 Feb[redacted]78

13. NUMBER OF PAGES 131

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS (of this report) UNCLASSIFIED 12 156p.

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Advanced Composites
Advanced Metallic Designs
Metal Matrix Composites
Landing Gear
Life Cycle Costs
Aircraft

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers the work performed under Air Force Contract F33615-76-C-3021, "New Concepts in Composite Material Landing Gear for Military Aircraft." Effort on Phase I was completed in August 1976. Phase II effort was redirected by a contractual change and was completed in February 1978.

Phase I effort included the selection of the B-1 Nose Gear as the baseline landing gear system and the conceptual design and evaluation of three concepts over

(CONT. ON REVERSE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

410 665

78 09 12 004

Gu

using composite material hardware. One concept was constrained by form, fit and function, one by fit and function, and the third by function only. The most effective gains in the use of composite material was when design freedom was increased and only the function constraint was used.

Phase II effort was redirected as a result of the Phase I results, and the main landing gear for the ATS advanced fighter, which is in the preliminary design stage, was selected as the baseline since it required only the function constraint. The scope of materials studied was increased, and Metal Matrix Composites and Advanced Metallics were studied, as well as Organic Advanced Composites. Designs were made, analyzed, and evaluated for each concept.

Evaluation indicated that Metal Matrix (boron/aluminum) Composite fabrication is not state-of-the-art for complex landing gear components. Both Organic Advanced (graphite/epoxy) Composites and Advanced Metallic (Superplastic formed and diffusion bonded titanium) Designs are viable concepts.

For the "volume limited" ATS aircraft, where the nacelle was increased to provide room for the larger advanced material landing gear, the Life Cycle Cost Analyses show that the Advanced Metallic (titanium) design will have the lowest cost, the baseline (high strength steel) is second, and the Organic Advanced Composite (Gr/Ep) design will have the highest life cycle cost. When selected parts, using advanced materials, are considered for an aircraft that is "not volume limited," the cost reduction due to lower weight reduces the production unit cost so that the Advanced Metallic (titanium) cost is lowest, the Organic Advanced Composite (Gr/Ep) is second, and the baseline high strength steel cost is the highest.

FOREWORD

This is Volume I, Technical Discussion, of a two volume Final Report which was prepared by the Los Angeles Division of Rockwell International, Los Angeles, California, under United States Air Force Contract F33615-76-C-3021, Air Force Project No. 2402, Task No. 240201, "New Concepts in Composite Material Landing Gear for Military Aircraft." The program is being administered by the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under the direction of Mr. J. Hampton (AFFDL/FEM).

This volume is the Final Report and contains the Technical Discussions covering work performed from April 1976 through February 1978. Volume II of the report contains the Appendices. Rockwell International personnel directly participating on the program were:

V. E. Wilson	Program Manager
F. W. Atkins	Systems Engineer
J. Rohlen	Structures Engineer
J. Kirkhoff	Contract Administration

The report was submitted in February 1978.

TABLE OF CONTENTS

Section		Page
I	INTRODUCTION	1
II	SUMMARY	6
	2.1 PHASE I	6
	2.1.1 Baseline	6
	2.1.2 Design Concepts	6
	2.1.3 Results	7
	2.2 PHASE II	9
	2.2.1 Baseline	9
	2.2.2 Conceptual Design Studies	13
	2.2.3 Preliminary Design	18
	2.2.4 Analysis and Evaluation	19
	2.2.5 Life Cycle Costs	24
III	BASELINE	25
	3.1 PHASE I BASELINE	25
	3.2 PHASE II BASELINE	25
	3.2.1 Design Requirements	26
	3.2.2 Baseline Main Landing Gear Description	30
	3.2.3 External Loads	31
	3.2.4 Component Loads	35
	3.2.5 Stress Analysis	35
	3.2.6 Weight	38
	3.2.7 Environmental Data	39
	3.2.8 Development Cost	39
	3.2.9 Production Cost	39
	3.2.10 Reliability	43
	3.2.11 Maintainability	43
	3.2.12 Safety	51
	3.2.13 Life Cycle Cost	53
IV	DESIGN STUDIES	55
	4.1 PHASE I DESIGN STUDIES	55
	4.2 PHASE II CONCEPTUAL DESIGN STUDIES	55
	4.2.1 Organic Advanced Composites System	56
	4.2.2 Metal Matrix Composite System	63
	4.2.3 Advanced Metallic System	79

TABLE OF CONTENTS - Continued

Section		Page
	4.2.4 Conceptual Design Studies Evaluation	90
	4.3 PHASE II PRELIMINARY DESIGN STUDIES	93
	4.3.1 Organic Composite Preliminary Design	93
	4.3.2 Advanced Metallic System Preliminary Design	103
V	ANALYSIS AND EVALUATION	112
	5.1 PHASE I - ANALYSIS AND EVALUATION	112
	5.2 PHASE II - Analysis and Evaluation	112
	5.2.1 Structural Analysis	112
	5.2.2 Producibility	115
	5.2.3 Installation Evaluation	118
	5.2.4 Weight	118
	5.2.5 Development Cost	118
	5.2.6 Production Cost	121
	5.2.7 Reliability	125
	5.2.8 Maintenance	127
	5.2.9 Evaluation	128
VI	LIFE CYCLE COSTS	133
	6.1 Phase I - Life Cycle Costs	133
	6.2 Phase II - Life Cycle Costs	133
VII	CONCLUSIONS AND RECOMMENDATIONS	138
	7.1 PHASE I - CONCLUSIONS	138
	7.2 PHASE II - CONCLUSIONS	138
	7.3 RECOMMENDATIONS	139

LIST OF FIGURES

Figure No.		Page
1	Task Flow Diagram	2
2	ATS Advanced Fighter	4
3	ATS Main Landing Gear	5
4	Structural Concept for Axially Loaded Struts	8
5	Baseline Configuration ATS Design Study	11
6	Study - Phase II Main Landing Gear Metallic Baseline	12
7	ATS Nacelle Constraints	13
8	Weight Analysis - Comparison	20
9	Development Cost Analysis - Comparison	21
10	Production Cost Analysis - Comparison	22
11	Selected Best Components - Cost Comparison	23
12	Life Cycle Costs Comparison Chart (Millions of 1977 Dollars)	24
13	Schematic of Typical Landing Gear Assembly and Location of Components	34
14	Landing Gear Study Production Cost Per Shipset	41
15	Cantilever "Leaf Spring" Concept	57
16	Dual Beam "Leaf Spring" Concept	59
17	Semi-Cantilever "Leaf Spring" Concept	60
18	Conventional Landing Gear Organic Advanced Composite	62
19	Study, Phase II ATS Main Landing Gear, Metal Matrix Composite Concept A and B.	67
20	Study, Phase II ATS Main Landing Gear Metal Matrix Composite, Concept C	69
21	Study, Phase II ATS Main Landing Gear Metal Matrix Composite Concept D	73
22	Study, Phase II ATS Main Landing Gear Metal Matrix Composite Concept E	77
23	Study, Phase II ATS Main Landing Gear Metal Matrix Composite Concept E	78
24	SPF/DB Titanium Expanded Sandwich Hardware	81
25	Trailing ARm Configuration (SPF/DB Titanium)	83
26	Four Bar Linkage Concept (SPF/DB Titanium)	85
27	Vertical Beam (SPF/DB Titanium)	86
28	Drag Link (SPF/DB Titanium)	87
29	Conventional Landing Gear Concept (SPF/DB Titanium)	89
30	Study, Phase II ATS Main Landing Gear Organic Composite	95
31	Strut Cylinder Filament Winding Tooling	98
32	Trunnion Support - Filament Winding Tooling	99
33	Piston/Fork Filament Winding and Forming Tooling	101
34	Study, Phase II ATS Main Landing Gear Advanced Titanium	105

LIST OF FIGURES - Continued

Figure No.		Page
35	Fork - SPF/DB Tooling	108
36	Strut Cylinder - SPF/DB Tooling	109
37	Wheel - SPF/DB Tooling	111
38	Landing Gear - Study-Production Cost Per Shipset (Unit Cost)	122

LIST OF TABLES

Table No.		Page
I	Baseline Life Cycle Costs (All costs in 1977 dollars)	13
II	Organic Advanced Composites Evaluation	15
III	Metal Matrix Composite Evaluation	16
IV	Advanced Metallic Evaluation	17
V	Material Systems Evaluation	18
VI	Evaluation Summary (Not Including Life Cycle Costs)	22
VII	Retraction and Extension Time	27
VIII	ATS Takeoff and Landing Conditions	32
IX	Summary of Main Landing Gear External Loads	33
X	Basic Material Properties 300M Steel	36
XI	Summary of Minimum Margins of Safety - 300M Steel Baseline Gear	37
XII	Weight Breakdown - ATS Main Landing Gear Baseline	38
XIII	Baseline Development Costs (RDT&E costs in thousands of 1977 dollars)	40
XIV	Production Cost - Baseline (1977 Dollars 500 Shipsets)	42
XV	Corrective Maintenance Demand Rates and Condemnation Rates	44
XVI	Servicing and Inspections Maintenance	46
XVII	Summary of Maintenance Demand Rates	47
XVIII	Summary Operational Support Equipment On-Aircraft Maintenance	48
XIX	Summary Operational Support Equipment Off-Aircraft Maintenance	49
XX	Baseline Support Costs - 10 Year Life Span	52
XXI	ATS Baseline Life Cycle Costs	54
XXII	Evaluation - Organic Advanced Composites Concepts	64
XXIII	Evaluation - Metallic Matrix Composite Concepts	80
XXIV	Evaluation - Advanced Metallics Concepts	91
XXV	Evaluation - Three Material Systems - Design Concepts	94
XXVI	Room Temperature Material Properties - 1980 Graphite/Epoxy	113
XXVII	Mechanical Properties at Room Temperature - SPF/DB Titanium	114
XXVIII	Summary of Minimum Margins of Safety - Graphite/Epoxy Composite Gear	116
XXIX	Summary of Minimum Margins of Safety - SPF/DB Titanium Gear	117
XXX	Weight Comparison - Material Systems by Landing Gear Component (ATS Main Landing Gear)	119
XXXI	Development Cost Comparison - RDT&E Cost (In Thousands 1977 Dollars)	120
XXXII	Landing Gear Unit Costs Comparison by Component (Thousands of 1977 Dollars/Side)	123

LIST OF TABLES - Continued

Table No.		Page
XXXIII	Production Cost Comparison (1977 Dollars) 500 Shipsets	124
XXXIV	Main Landing Gear Alternate Concept Reliability Comparison	126
XXXV	Support Cost Comparison - 10 Year Life Span - Costs in Thousands of 1977 Dollars	129
XXXVI	Component Part Weight Comparison (Weight in Pounds/Side	130
XXXVII	Component Part Unit Cost Comparison with Weight and Growth Effects (on a "nonvolume limited" aircraft)	132
XXXVIII	Life Cycle Costs by Category (In Thousands of Dollars)	134
XXXIX	Total Life Cycle Costs (In Thousands of Dollars)	136

SECTION I

INTRODUCTION

A number of advanced material systems are currently being studied under both private industry and Air Force programs. These systems are in various stages of development, but all have superior qualities which may prove advantageous for use in landing gear components. The objective of this program was to explore the extent to which these advanced materials could be used in a complete landing gear system, and the cost and weight benefits that could result from this usage.

This program is phase oriented with this final report covering both Phase I and Phase II. Phase I work was performed between April and August 1976. Phase II work was performed between April 1977 and February 1978. A Phase I and Phase II task flow diagram is shown in figure 1.

The program was contractually reoriented after Phase I had been completed. Phase I studied only composite materials, but under three different levels of constraint, while after redirection, Phase II studied three different material systems, but used only the "function" constraint.

Phase I of the program was orientated to composites since the Air Force through AFFDL, has sponsored a number of successful composite landing gear hardware programs. These have established the feasibility of using composite material for certain landing gear components, but all hardware designed was constrained by "form, fit and function." Phase I of this program has three separate sections so that hardware was designed under three distinct levels of constraint. The first is "Substitution," with "form, fit and function" constraints. The second section is "modification" with both "fit and function" constraints. The third section is "redesign" with only the "function" constraint.

The approach used for the Phase I section followed the task outline shown in figure 1 and resulted in the choice of the B-1 nose landing gear as the baseline. Conceptual designs for composite landing gear hardware were developed for each section and level of constraint as described above. Methodology to be used in preliminary design and analysis was defined and documented. The design concepts created in Phase I were evaluated and this showed that reduction in constraints allowed more parts to be made from composites.

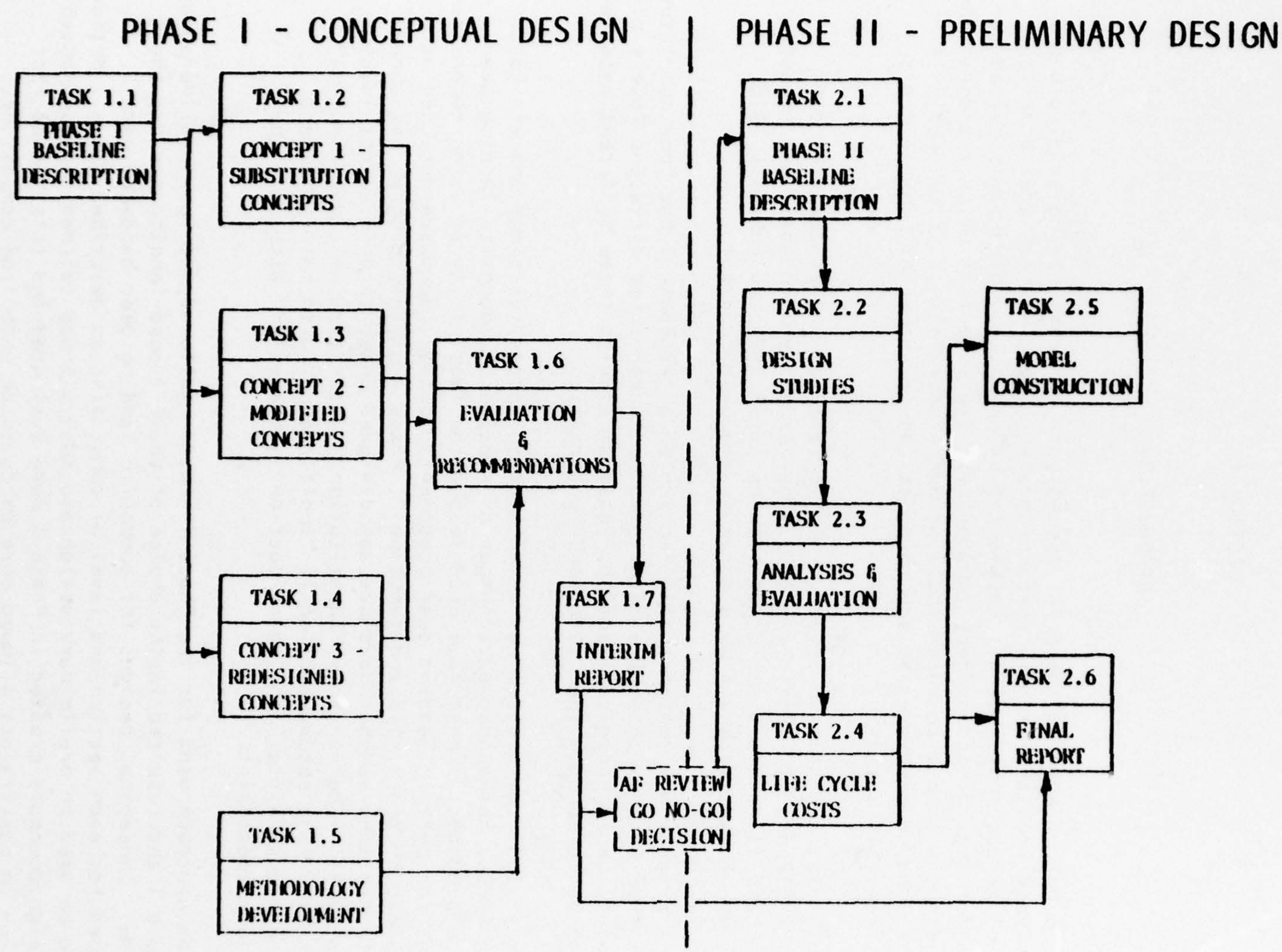


Figure 1. Task Flow Diagram

Phase II followed the task outline shown in figure 1. The results from Phase I indicated that since fewer constraints were important to the program purpose of maximum usage of advanced material systems in a landing gear, Phase II should use a new baseline with only the "function" constraint. The scope of Phase II was widened to include a metal matrix composite system and an advanced metallics system as well as the organic advanced composite system.

The new baseline requirement for Phase II was to use the main landing gear proposed for the Air-To-Surface (ATS) advanced fighter program, see figure 2. The ATS main landing gear has been the subject of a preliminary design study under a separate Rockwell ATS study program, see figure 3. This baseline has been defined and the design parameters and constraints presented.

Conceptual designs for landing gear hardware were developed using all three material systems and evaluated. The two best material systems were then selected and preliminary designs made. Analysis and evaluation of these designs were made to gather data for weight, cost and life cycle cost studies.

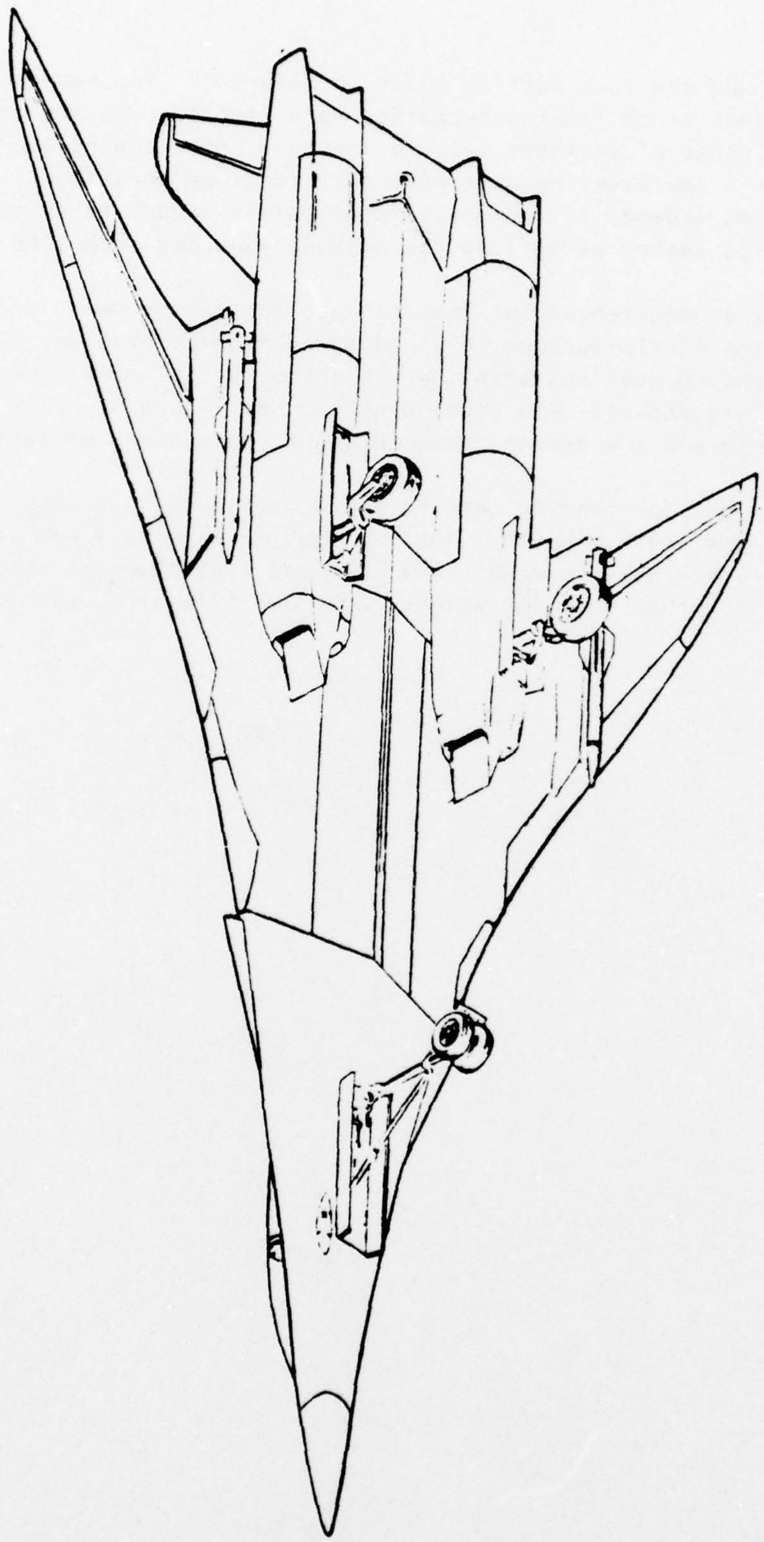


Figure 2. ATS Advanced Fighter

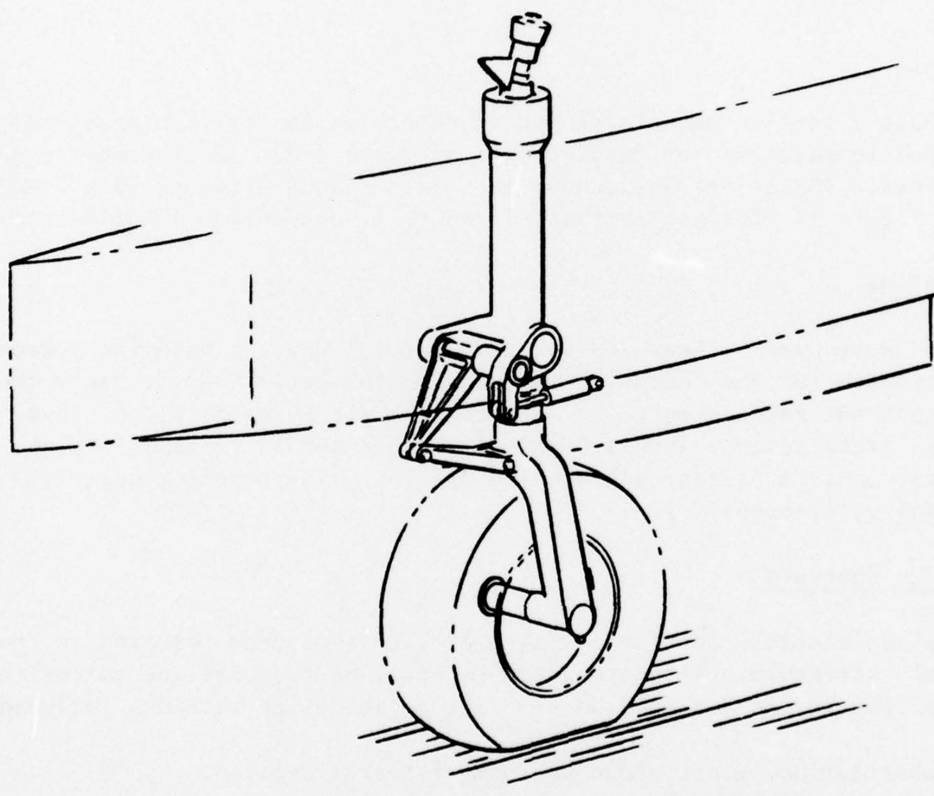


Figure 3. ATS Main Landing Gear

SECTION II

SUMMARY

This report describes the effort conducted on both Phase I and Phase II of Air Force Contract No. F33615-76-C-3021, "New Concepts in Composite Material Landing Gear for Military Aircraft."

2.1 PHASE I

The Phase 1 section was structured to determine the maximum practical use of composite material for landing gear hardware under three specific sets of constraints. The effort was conducted in accordance with the Task Flow Diagram of figure 1. The entire Phase I report is presented in Appendix A.

2.1.1 Baseline

The B-1 Nose Landing Gear was selected for the Phase 1 baseline system and the rationale for the selection was made on the basis that it meets the following contract requirements; it is a current Air Force airplane, (over 175,000 lbs. gross weight) and is completely described in terms of design requirements, constraints and engineering drawing. The baseline gear is described fully in Appendix A.

2.1.2 Design Concepts

The Design Concepts section of Phase I of this program resulted in the selection of intermediate strength graphite/epoxy as the baseline composite material for use in the design studies. The three design sections included:

1. Substitution, constrained by form, fit and function;
2. Modified, constrained by fit and function; and
3. Redesigned, constrained by function only.

These designs were qualitatively evaluated for materials, structures, design integrity, fabrication, weights and cost and a summary of these evaluations is presented in Section VI, page 92 of the phase 1 Report, Appendix A. A summary of conclusions reached appears in the following.

<u>2.1.2.1 Concept 1 - Substitution (form, fit and function)</u> - Baseline information and drawings of B-1 nose gear metallic hardware was studied and conceptual design drawings were made for composite and composite/metal parts which have identical key dimensions, and can be substituted on a part-for-part basis for the baseline metallic hardware. Some of these concepts were

designed to have composite material spliced to metallic end fittings to meet the high load requirements within the form constraint. All designs studied in this section were evaluated as viable except the torque links which were considered very high technical risk parts.

2.1.2.2 Concept II - Modified (fit and function) - Existing structural attachments were used, but kinematics of the drag braces and down lock links were revised to allow increased usage of composites. It was determined for this concept that the piston and the lower end of the strut cylinder must remain metallic since the larger diameter required for composite parts would result in having to spread the nose wheels which would violate the stowage limit (fit) constraint. All composite designs studied in this section were evaluated as viable.

2.1.2.3 Concept III - Redesigned (function) - Studies were made to evaluate the use of landing gear concepts which were allowed to differ from the baseline system in kinematics, attachment location and storage volume. A "leaf spring" concept was studied and evaluated as a very high technical risk and not weight effective. The size of the B-1 nose gear is an important factor against usage of this concept, but the "leaf spring" gear configuration may prove to be a viable weight effective system on a smaller fighter airplane.

A conceptual design was made of a "trailing arm" nose gear, but it requires a large change in storage volume and did not appear to have any major advantages. The study using the same concept as the baseline and only slightly changed kinematics, provided a nose gear system which allowed the maximum use of composite material while restricting changes to a minor widening of the nose gear wheel well. The wheels on this study were moved farther apart to allow room for a composite piston and strut. All designs evaluated for this study were viable except for the piston which was considered a very high technical risk.

2.1.3 Results

The general results of the Phase I effort show that the most effective gains in the use of composite structure occur in the "Redesign" Concept III, Section where more design freedom is allowed. This is because space limitations are removed which restrained the use of composites in some areas of the landing gear structure. Concept I and II resulted in more compromises in the design because of increased restrictions and a lesser use of composite structure. However, the concepts developed will still generally result in cost effective hardware, but to a lesser extent, based on the limited evaluation performed in Phase I.

Many structural elements of landing gear hardware are axially loaded and the weight effective "race track" configuration was used similar to that used in previous composite landing gear programs. This configuration, as previously used, has inherent structural weaknesses near the end of the member where large interlaminar shear forces occur between the "race track" and the web reinforcements. A solution to this problem is shown in figure 4, which uses a series of "race tracks" interleaved with shear webs, and should significantly improve the strength and fatigue properties of the "race track" configuration.

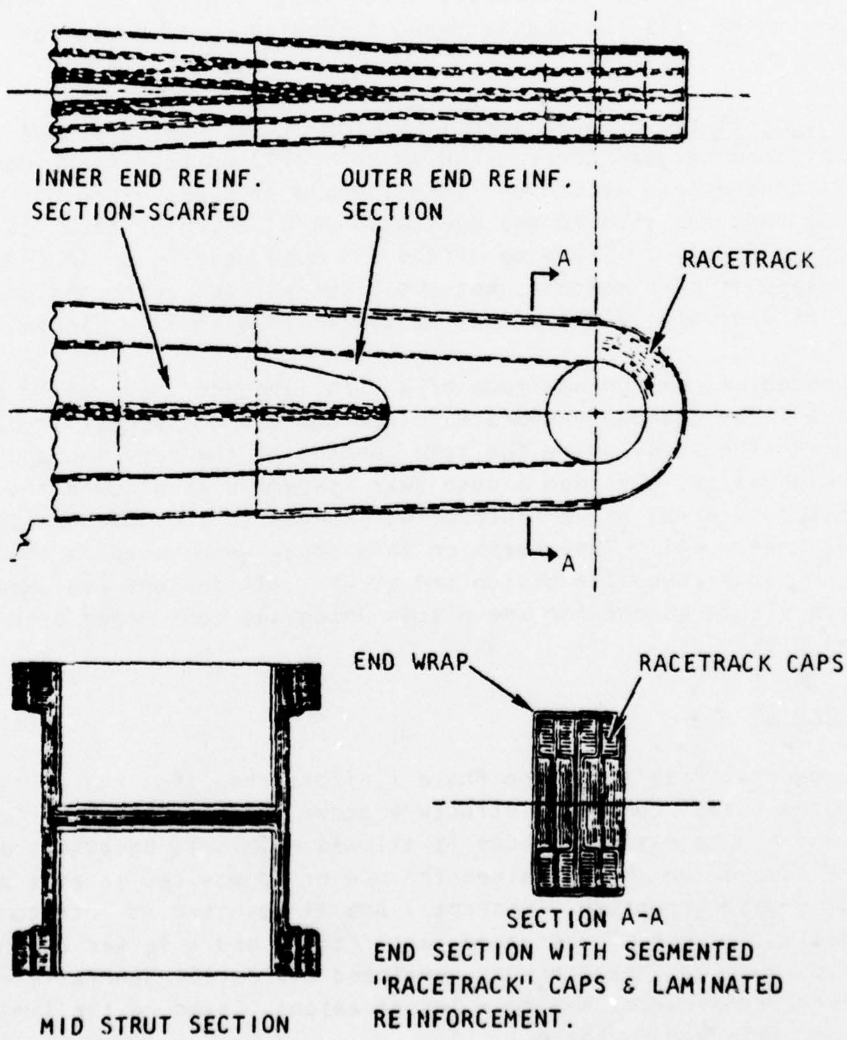


Figure 4. Structural Concept for Axially Loaded Struts

2.2 PHASE II

The Phase II section of the program is structured to determine the advantages of advanced materials and concepts in the design of a landing gear where constraints are minimized. Three advanced material systems were studied: Organic Advanced Composites, Metal Matrix Composites and Advanced Metallics. The baseline used was the main landing gear of the ATS advanced fighter airplane. This airplane is in the advanced design stage where "function" is the only constraint needed. The effort was conducted in accordance with the Task Flow Diagram of figure 1.

2.2.1 Baseline

The use of the ATS main landing gear as the baseline was specified by contractual change for Phase II of this program. The baseline information on this landing gear was obtained from a separate Rockwell ATS study program. A fleet of 500 ATS aircraft with a 10 year life span was assumed.

The ATS airplane has a tricycle type landing gear configuration which consists of a nose gear and two main landing gear assemblies designed for a 53,000 pound gross weight airplane. The baseline main landing gear was state-of-the-art metallic materials. Each of the single wheel assemblies is mounted in the engine nacelle and is fully retractable aft by a hydraulic actuator. This landing gear will provide the required ATS performance for landing, take-off and flotation, and has been designed to comply with the ground handling requirements of MIL-A-8862.

The baseline landing gear assembly consists of a semi-cantilevered shock strut with a single tire and wheel mounted in the island of the split engine air intake duct in the nacelle. The landing gear is attached to the nacelle structure by jornaled trunnions at the lower end of the strut main body and latched into extended and retracted positions by a locking device at the top of the strut. See figure 3.

The strut shock absorber is an air-oil type in which the passage of metered oil through an orifice is used to absorb landing impact energy and to control the rate of compression. A snubber valve controls the rate of extension of the piston.

The shock strut complies with the requirements of MIL-L-8552, MIL-T-6053 and AFSC DH2-1 and is capable of withstanding the loads derived from MIL-A-8860, MIL-A-8862, MIL-A-8866 and MIL-A-8867, including static strength and four lifetime fatigue requirements.

The air vehicle design sinking speed used was 10 feet per second at the landing design weight and 6 feet per second at the maximum design landing

weight. The shock strut has been designed with a vertical stroke of 12 inches and a designed 4 inch stroke from static to compressed position.

Dimensional constraints for the ATS landing gear are shown in figure 5, the ATS Air Vehicle Configuration drawing and hardware dimensions on figure 6, the ATS Baseline Main Landing Gear drawing.

The baseline main landing gear loads were derived from an ATS study which generated the loads using a computer program - "Structural Weight Estimation Program" (SWEEP). The baseline configuration is considered structurally adequate since no negative margins of safety were determined by a stress analysis.

The weight of the ATS main landing gear was calculated to be 582 pounds for each side or a total of 1164 pounds per ship set.

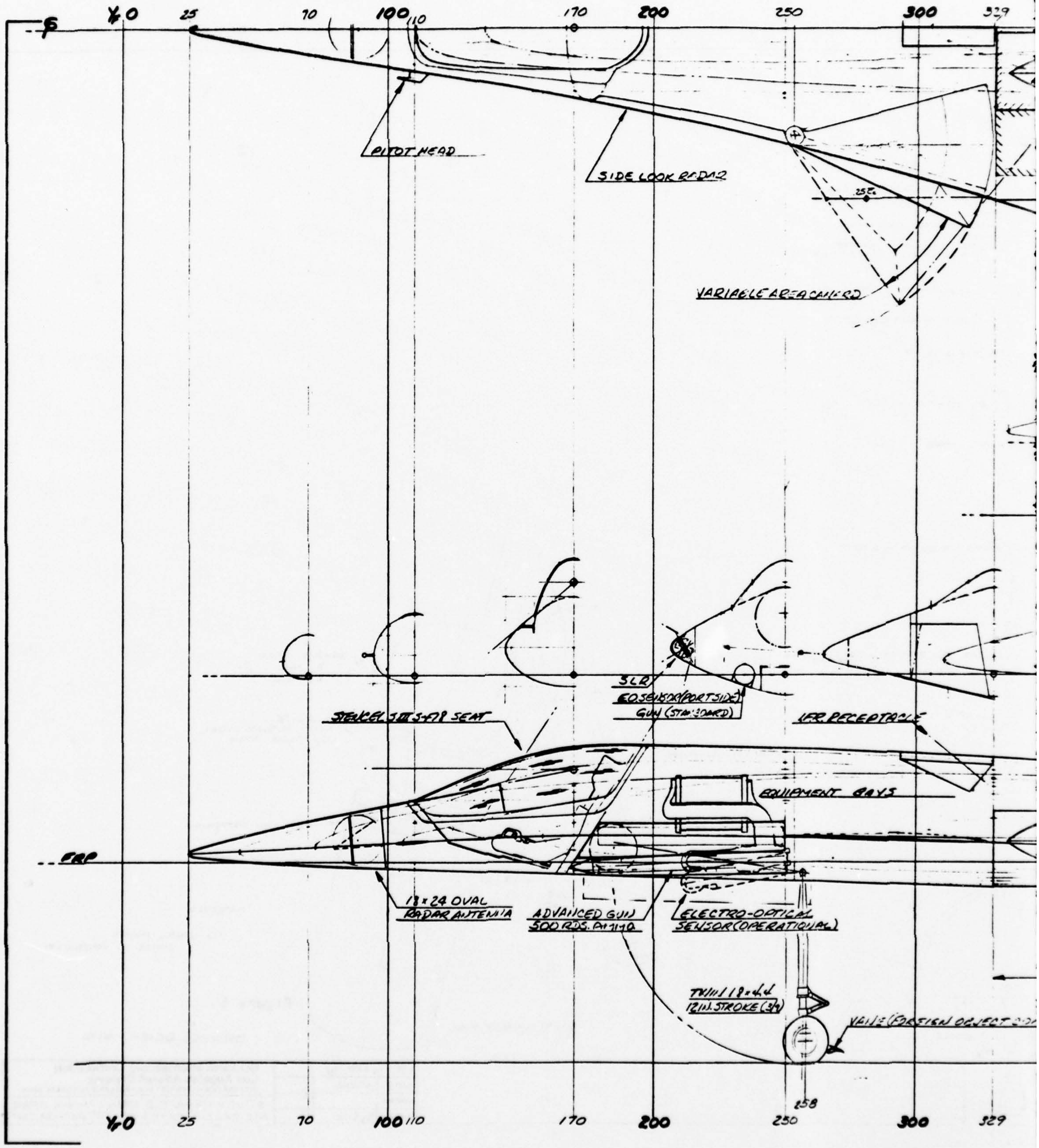
Production cost estimates were made for the ATS main landing gear component parts. For fabrication costs an 89% learning curve and a 92% cost reduction curve were used. The nonrecurring costs were $590,000 (1977 dollars) and the recurring costs were $40,550,000, adding to $41,140,000 total production costs. The cumulative unit average cost at unit 500 is $82,300 per ship set.

Two reliability factors were determined for the baseline ATS landing gear; the Maintenance Demand Rate (MDR), which is 24,330 per 10^6 flight hours and the Condemnation Rate which is 2840 per 10^6 flight hours. The MDR represents a Mean Time Between Corrective Maintenance Action (MTBCMA) of 41 flight hours.

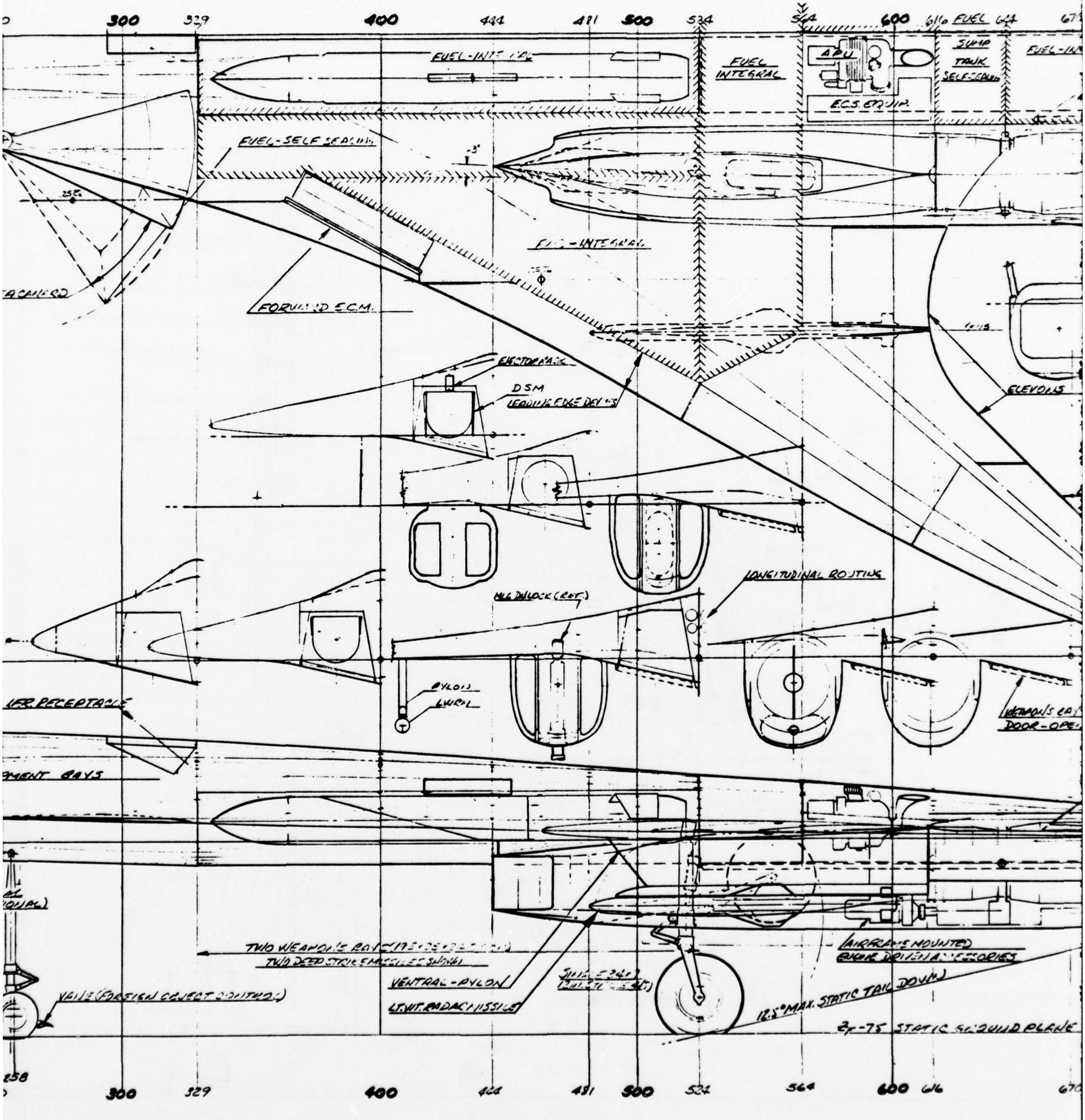
The maintenance and logistics support costs for the fleet of 500 aircraft over a life span of 10 years will be $6,150,000 spares cost and $3,680,000 personnel cost, making total support costs of $9,830,000.

A safety hazard caused by stress corrosion related accidents reported by the Air Force was estimated to result in a predicted cost of $18,105,000 over a 10 year period for the ATS airplane.

Life Cycle Costs (LCC) include the sum of development, production, accident costs and support costs. Development costs will be $977,000 for engineering, $378,000 for production of two ship sets and $150,000 for tooling. Total development cost will be $1,505,000. The Production cost will be $41,139,000. The accident cost will be $18,105,000. The total support cost will be $9,828,000. The Life Cycle Cost will be $70,577,000 for a 500 aircraft fleet for a period of 10 years. See table 1.

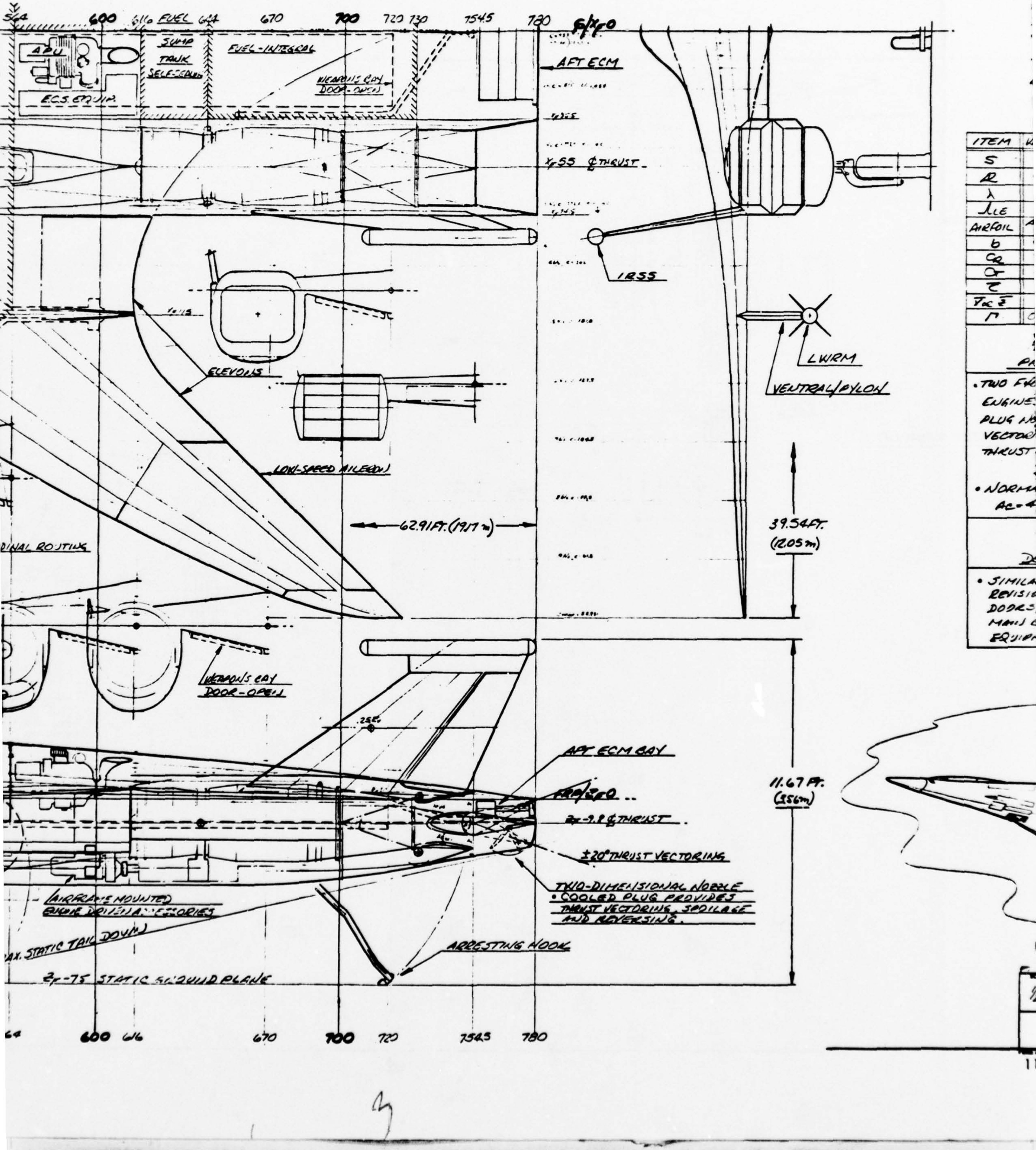


PITOT HEAD
SIDE LOOK RADAR
EQUIPMENT BAYS
13 x 24 OVAL
RADAR ANTENNA
ADVANCED GUN
ELECTRO-OPTICAL
SENSOR (OPERATIONAL)
FRP

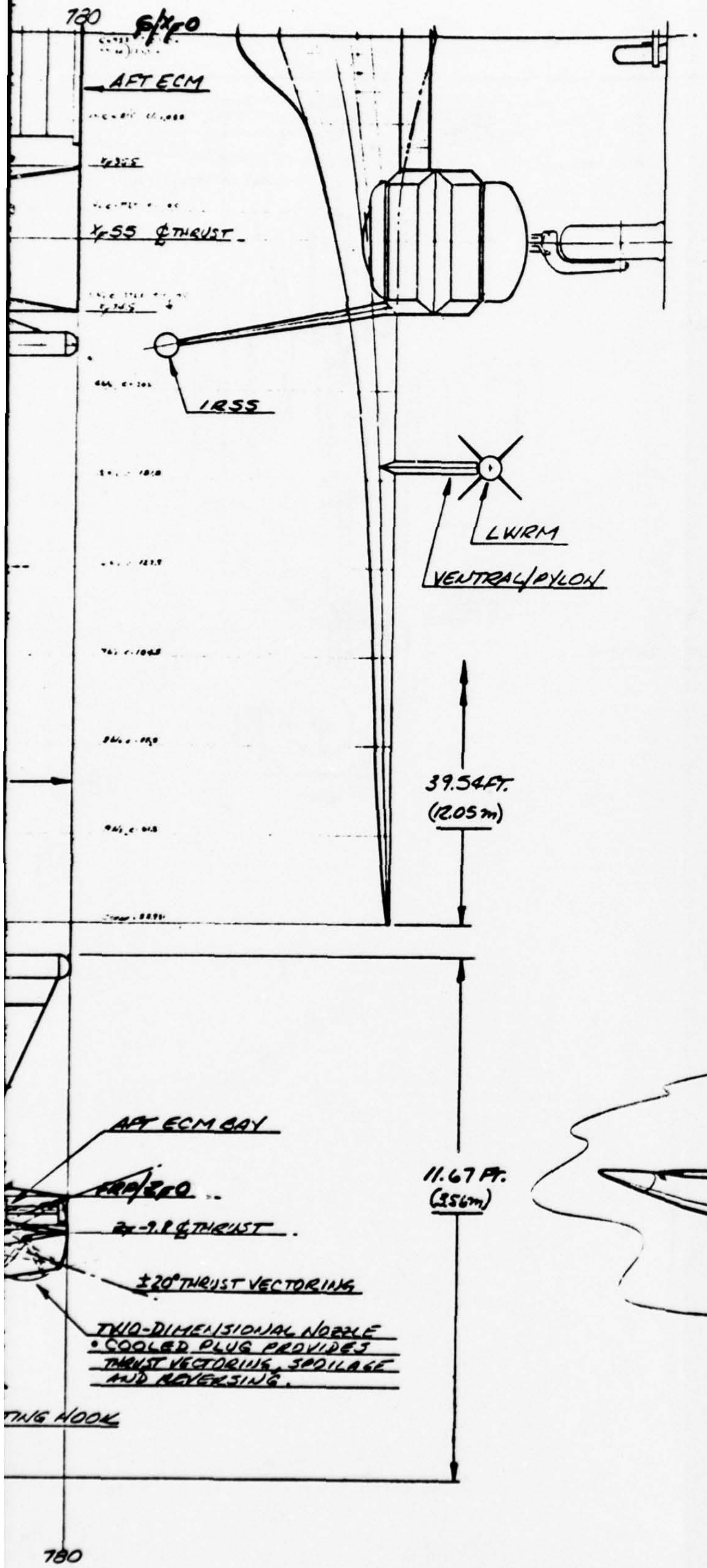


300
329
400
444
481
500
524
564
600
616
644
FUEL
SUMP
TANK
APU
E.C.S. EQUIP.
FUEL
INTEGRAL
FUEL-SELF SEALING
-3°
FORWARD E.C.M.
EJECTOR RACK
DSM
LEADING EDGE DEVICES
ELEVONS
LONGITUDINAL ROUTING
PYLON
IFR RECEPTACLE
VENTRAL-PYLON
LT.WT. RADAR MISSILE
AIRFRAME MOUNTED
ENGINE DRIVEN ACCESSORIES
12.5° MAX. STATIC TAIL DOWN
STATIC GROUND PLANE
258
300
329
400
444
481
500
524
564
600
616

2



600
616 FUEL 644
670
700
720 730
754.5
780
SUMP TANK SELF-SEALING
FUEL-INTEGRAL
APU
ECS EQUIP.
WEAPONS BAY DOOR-OPEN
AFT ECM
Y_F55 ¢ THRUST
IRSS
ELEVONS
LWRM
VENTRAL/PYLON
LOW-SPEED AILERON
62.91 FT. (19.17 m)
39.54 FT. (12.05 m)
DINAL ROUTING
WEAPONS BAY DOOR-OPEN
AFT ECM BAY
FRP/Z=0
Z_F-9.8 ¢ THRUST
±20° THRUST VECTORING
TWO-DIMENSIONAL NOZZLE
• COOLED PLUG PROVIDES THRUST VECTORING, SPOILAGE AND REVERSING.
11.67 FT. (3.56 m)
AIRFRAME MOUNTED ENGINE DRIVEN ACCESSORIES
MAX. STATIC TAIL DOWN
ARRESTING HOOK
Z_F-75 STATIC GROUND PLANE
564
600 616
670
700 720
754.5 780
ITEM
S
A
λ
Λ_{LE}
AIRFOIL
b
C_R
C_T
$\bar{c}$
$Y_{@\bar{c}}$
Γ
• TWO F... ENGINES PLUG NO... VECTOR... THRUST...
• NORMA... Ac-4...
• SIMILA... REVISIO... DOORS... MAIN ... EQUIP...



GEOMETRIC DATA

ITEM	WING (TRAPEZOID)	VERT. TAIL	VENTRAL/PYLON	CANARD
S	460 FT²	27 FT² EA. (TRUE)	18.5 FT² EACH	37 FT² EXPOSED
Æ	3.4	1.0	0.198	2.61
λ	0.25	0.35	0.828	∞
Λ_{LE}	60°	55°	42°	35°
AIRFOIL	AERO. DEFINITION t/c AS TABULATED	64A004	[illegible]	AERO. DEFINITION [illegible]
b	474.569	62.352	23.0	118
C_R	223.326	92.376	126.5	91
C_T	55.831	32.331	106	0
$\bar{c}$	156.328	67.172	116.55	60.666
$Y_{\bar{c}}$	94.714	26.172	11.162	19.667
Γ	0° LOWER SURFACE [illegible]	80°	—	4°

PROPULSION

- TWO F404-GE-400 TURBOJET ENGINES WITH TWO-DIMENSIONAL PLUG NOZZLES INCORPORATING THRUST VECTORING, THRUST SPOILAGE AND THRUST REVERSING.
- NORMAL SHOCK INLETS A_c = 482 SQ. IN. EACH

DESIGN SUMMARY

- SIMILAR TO D619-3 EXCEPT FOR REVISIONS TO WEAPONS BAYS DOORS, CANARD GEOMETRY, MAIN LANDING GEAR AND EQUIPMENT LOCATIONS.

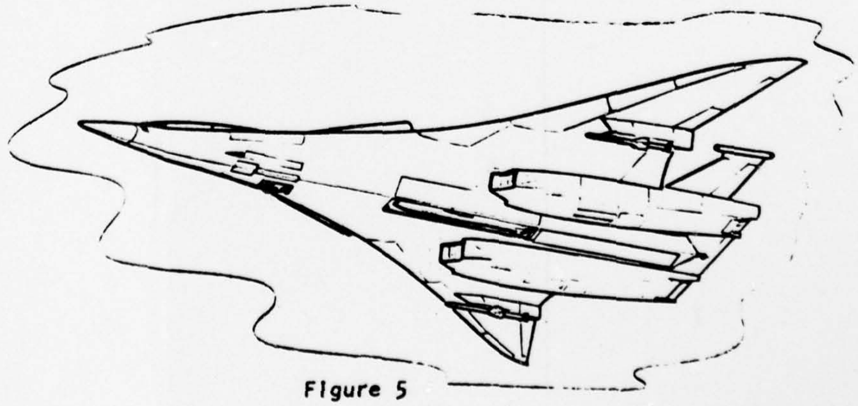


Figure 5

SCALE 1/20	DR. HENDRIX DATE 2 [illegible] 1977 MODEL 3146	Los Angeles Aircraft Division, Rockwell International, INTERNATIONAL AIRPORT · LOS ANGELES, CALIFORNIA	ADVANCED DESIGN
	BASELINE CONFIGURATION ATS DESIGN STUDY		D619-3A

4

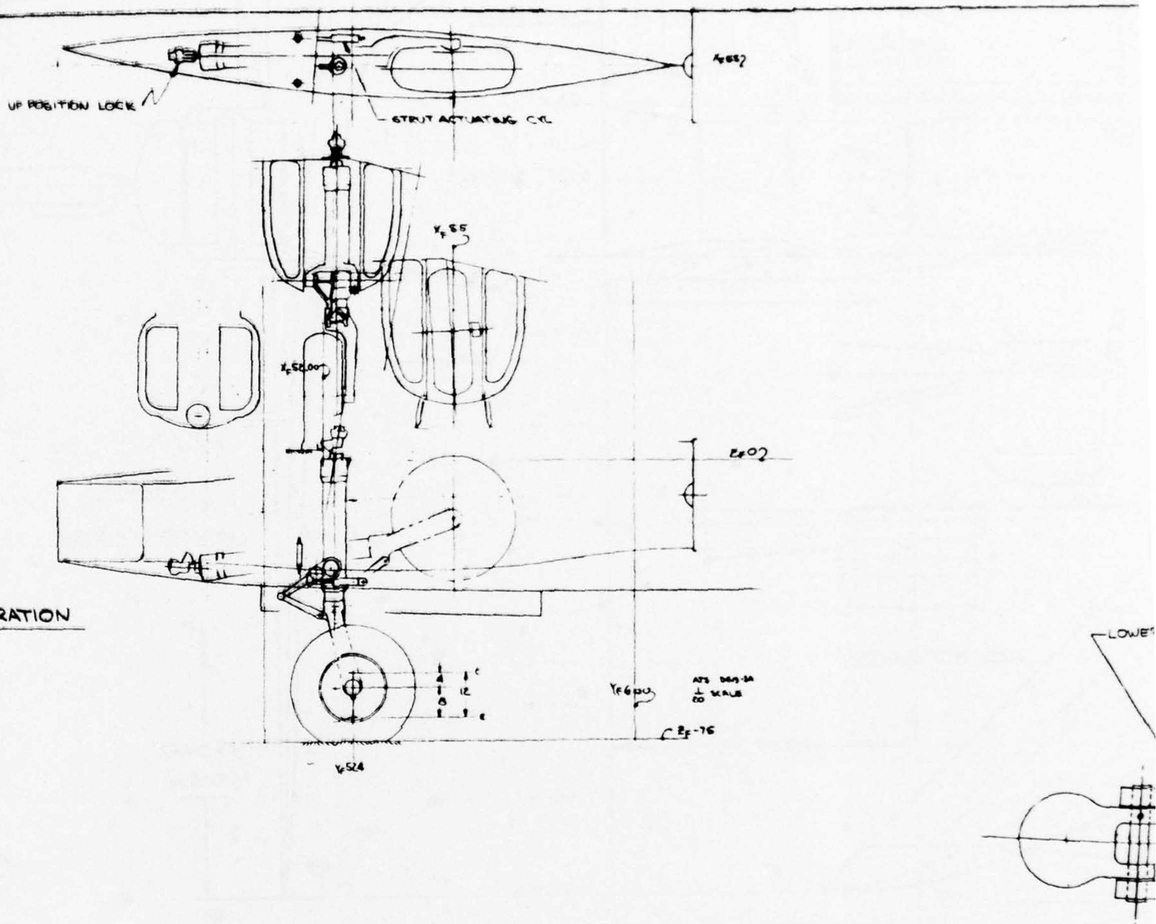
BASE DATA —

W_{TO}	53000	LBS
W_L	47700	LBS
V_L	120	KTS
V_{TO}	160	KTS

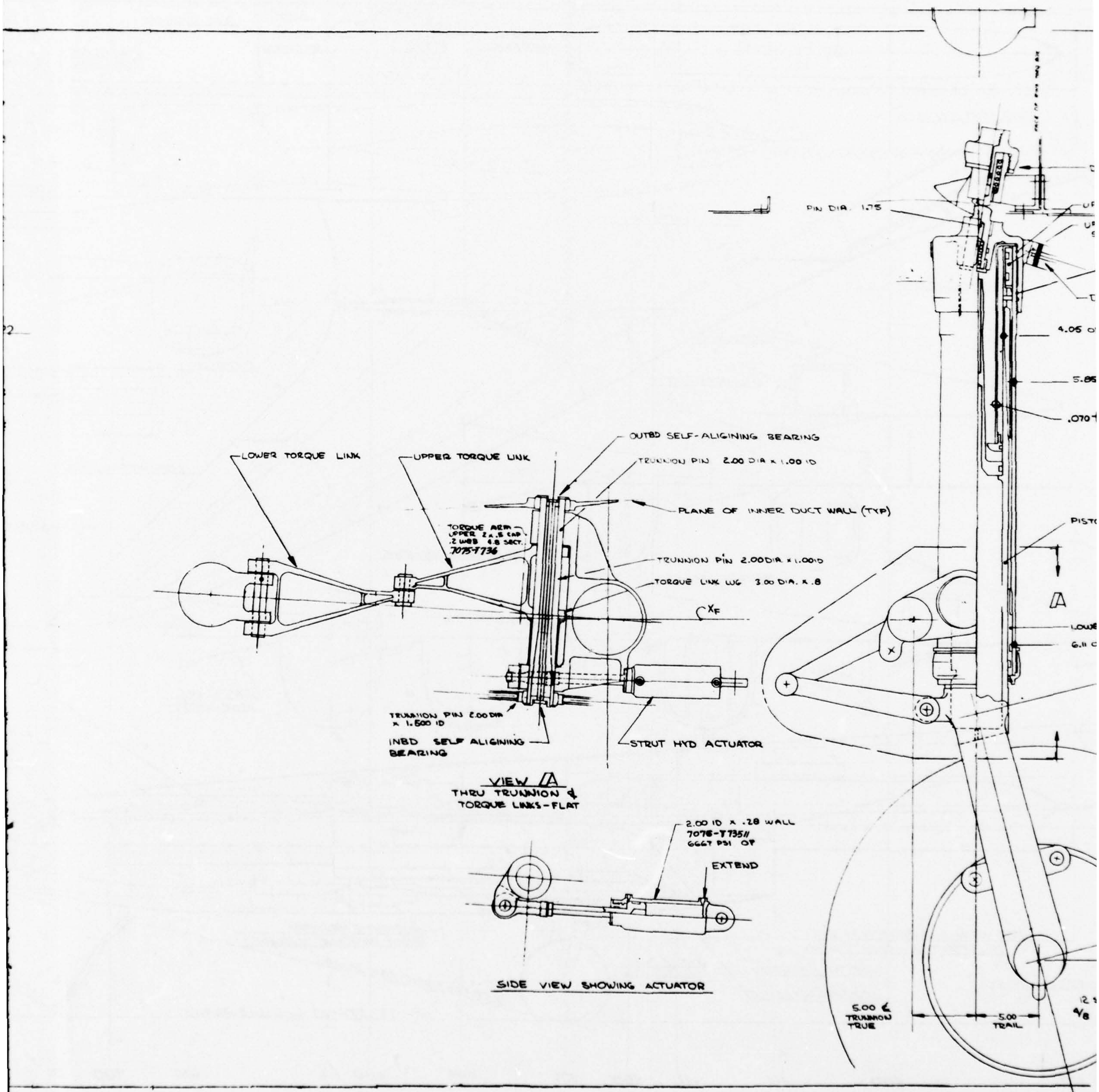
34x9.9 TIRE 270 PSI

BRAKE — CARBON DISC/ROTOR

KE/BRAKE ≈ 32700000



GENERAL CONFIGURATION



VIEW A
THRU TRUNNION & TORQUE LINKS-FLAT

SIDE VIEW SHOWING ACTUATOR

J

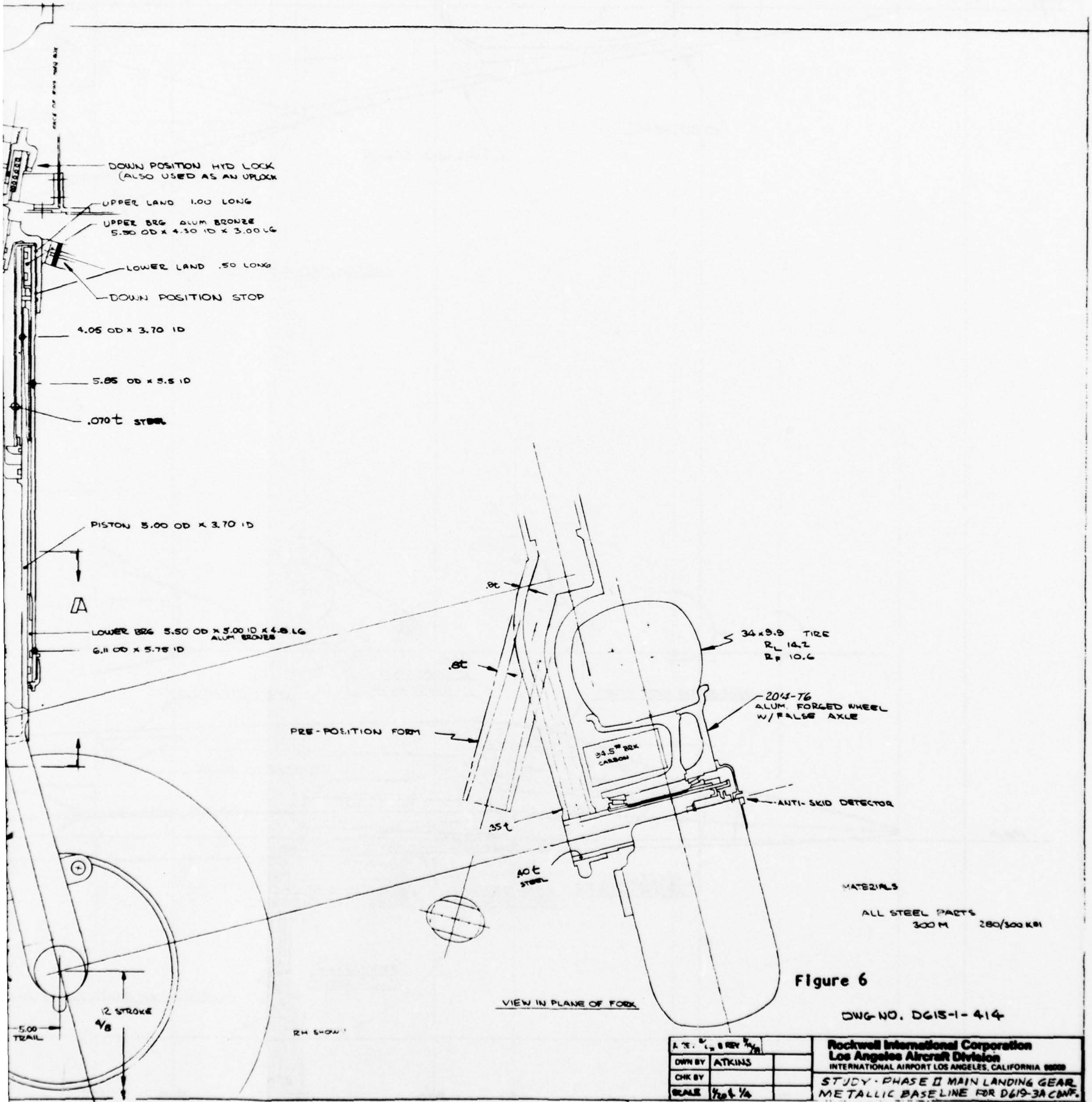

DOWN POSITION HYD LOCK
(ALSO USED AS AN UPLOCK
UPPER LAND 1.00 LONG
UPPER BRG ALUM BRONZE
5.50 OD x 4.30 ID x 3.00 LG
LOWER LAND .50 LONG
DOWN POSITION STOP
4.05 OD x 3.70 ID
5.85 OD x 5.5 ID
.070 t STEEL
PISTON 5.00 OD x 3.70 ID
A
LOWER BRG 5.50 OD x 5.00 ID x 4.8 LG
ALUM BRONZE
6.11 OD x 5.75 ID
.8t
.8t
34 x 9.9 TIRE
R_L 14.2
R_F 10.6
2014-T6
ALUM. FORGED WHEEL
W/FALSE AXLE
PRE-POSITION FORM
34.5 BRK
CARBON
ANTI-SKID DETECTOR
.35 t
.40 t
STEEL
MATERIALS
ALL STEEL PARTS
300 M 280/300 KSI
5.00
TRAIL
12 STROKE
4/8
RH SHOWN
VIEW IN PLANE OF FORK
DWG NO. D615-1-414
DWN BY ATKINS
CHK BY
SCALE 1/20 & 1/4
Rockwell International Corporation
Los Angeles Aircraft Division
INTERNATIONAL AIRPORT LOS ANGELES, CALIFORNIA 90009
STUDY - PHASE II MAIN LANDING GEAR
METALLIC BASELINE FOR D619-3A CONF.

Figure 6

3

TABLE 1

BASELINE LIFE CYCLE COSTS
(All costs in 1977 dollars)

Total Development Costs	$ 1,505.000
Total Production Costs	41,139,000
Total Accident Costs	18,105,000
Total Support Costs	$ 9,828,000
Total Life Cycle Costs	$70,577,000

2.2.2 Conceptual Design Studies

Design studies of the main landing gear on the ATS advanced fighter aircraft were made using only the "function" general constraint. However, other trade study factor constraints include: extended wheel position for landing performance; landing gear trunnion location for structural considerations; wheel well location and size for engine air intake duct size, lines and performance; and nacelle size, shape and location with respect to the weapons bay clearance fall line, see figure 7.

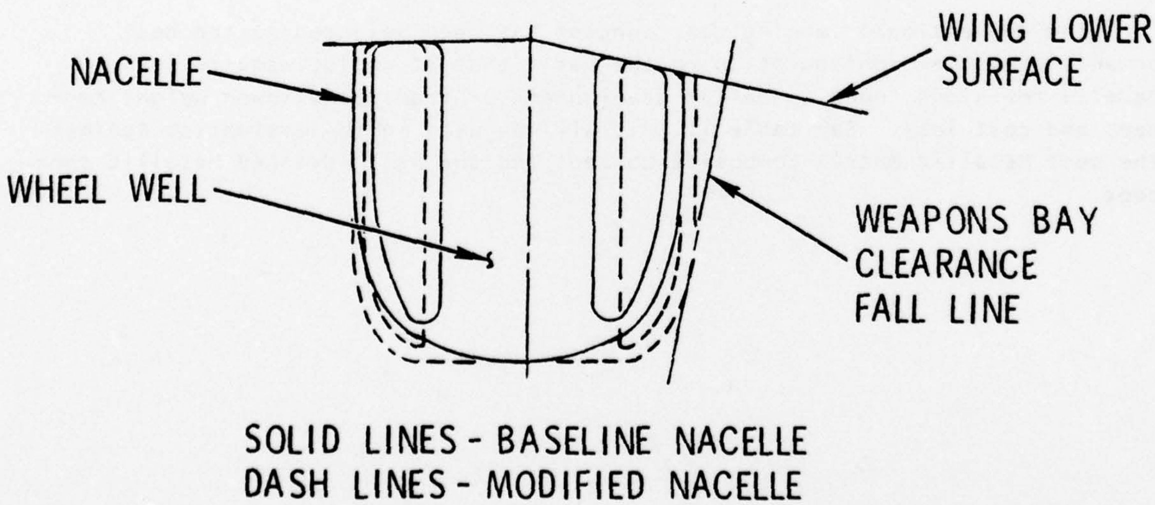


Figure 7. ATS Nacelle Constraints

Conceptual designs were made using the three material systems; Organic Advanced Composites, Metallic Matrix Composites and Advanced Metallics. These conceptual designs were then evaluated within each material system to select the best configuration.

2.2.2.1 Organic Advanced Composites System - Intermediate strength graphite/epoxy (Gr/Ep) composite material was selected on the basis that it provides a good balance between strength and cost. Four concepts were studied using this material. They included the "leaf spring" configuration in which the landing impact energy is absorbed by beam deflection, and the conventional configuration which uses an air-oil shock strut to absorb the energy.

Three concepts were studied using the "leaf spring" configuration. They were; a cantilever leaf spring concept, a dual beam leaf spring concept, and a center support beam leaf spring concept. All of these concepts used flat composite plates bonded to a resilient material between them. The composite plates will deflect under load to absorb the kinetic energy of the landing and the hysteresis property of the resilient material between the leaves will reduce the high energy return (reflex action) of the leaf spring.

The conventional landing gear concept uses a configuration similar to the baseline landing gear, see figure 3. It has a semi cantilevered shock strut which uses an air-oil type shock absorption system. The increased size requirements for using Gr/Ep composite resulted in a strut 9.8 inches outside diameter compared to 5.85 inches for the baseline.

The conventional landing gear concept has been selected as the best organic composite configuration on the basis that it would; require less nacelle revisions, need a smaller development program, be a lower weight concept and cost less. See table II. It will be used in the evaluation against the best Metallic Matrix Composite concept and the best Advanced Metallic concept.

TABLE II

ORGANIC ADVANCED COMPOSITES EVALUATION

Concept	Development Program	Nacelle Revisions	Weight Estimates	Cost Estimates
Cantilever	Major	Very Extensive	Heavy	Very High
Dual Beam	Major	Very Extensive	Heavy	Very High
Center Support Beam	Major	Very Extensive	Heavy	Very High
Conventional Landing Gear	Minor	Moderate	Lightest	Moderate

2.2.2.2 Metal Matrix Composite System - The metal matrix composite selected for this study was boron/aluminum (B/Al) since it is closer to state-of-the-art, and has more material and design data available than other metal matrix composites.

Five conceptual designs have been made. They include:

1. Concept A which has a folding drag link with a single wheel.

2. Concept B which also uses a folding drag link, but has dual wheels.

3. Concept C which has a vertical air-oil shock strut mounted on two retracting links with a forward nonfolding drag strut.

4. Concept D which is a trailing arm configuration with the shock strut mounted near the center of the beam.

5. Concept E which is a conventional landing gear configuration similar to the baseline. See figure 19 through 23.

Concept E, the conventional landing gear configuration, has been selected as the best Metal Matrix Composite design to be evaluated against the best Organic Advanced Composite design and the best Advanced Metallic design. The choice of Concept E was made because it has fewer parts, required less changes to the nacelle and would be lighter and less costly. See table III.

TABLE III

METAL MATRIX COMPOSITE EVALUATION

Concept	Nacelle Structure Revisions	Weight Estimates	Cost Estimates
A	Very Extensive	Heavy	Not a viable concept
B	Extensive	Heavy	Very High
C	Major	Heavy	High
D	Major	Heaviest	High
E	Minor	Lightest	Lowest

2.2.2.3 Advanced Metallic System - Titanium using the superplastic formed and diffusion bonded (SPF/DB) fabrication processes has been selected as the advanced metallic system to be used in this study because complex, structurally efficient parts can be economically manufactured.

This process is based on the superplasticity and diffusion bonding properties of titanium which occur under identical conditions and allow the superplastic forming and diffusion bonding to take place concurrently within the die cavity.

Three different landing gear configurations have been conceptually designed for this study. See figures 25, 26, and 29.

1. A "trailing arm" configuration with the wheel mounted in a double fork at the end of the beam which is supported by trunnions at the forward end and the shock absorber near the center of the beam.

2. A "four bar linkage" concept consisting of a vertical beam which supports the wheel, a drag brace lower link and an upper link, which, with the nacelle structure, makes up the four bar linkage.

3. A conventional landing gear similar to the baseline configuration.

The conventional landing gear concept has been selected as the best design because it has fewer parts, will be lighter, will require less nacelle revisions and it will cost less. See table IV for a summary of the evaluattions. This design will be evaluated against the best Organic Advanced Composite design and the best Metal Matrix design.

TABLE IV

ADVANCED METALLIC EVALUATION

Concept	Nacelle Structure Revisions	Weight Estimate	Cost Estimate
Trailing Arm	Major	Heaviest	Highest
Four Bar Linkage	Moderate	Moderate	Moderate
Conventional Land Gear	Minor	Lightest	Lowest

2.2.2.4 Design Studies Evalualtion - The best conceptual designs made for each of the three material systems have been evaluated. Since the best concept of each material system was the conventional landing gear configurations, the "function" constraint was equally met. More nacelle revisions are required for the Organic Advanced Composite concept than for the other material systems.

Boron/aluminum metal matrix thin walled tubes using unidirectional tape, which are axially loaded, have been successfully fabricated in production, but the parts required for the landing gear are heavy walled tubes which must have cross plied laminate orientations to give multi-axial load carrying capability. Since no information can be located, it is evident that little or no fabrication of complex, heavy walled metal matrix parts have been done.

The extensive development program required and the very high producibility risk assigned to the Metal Matrix Composite system led to the recommendation to stop the design effort on this system. See table V for the evaluation summary.

TABLE V

MATERIAL SYSTEMS EVALUATION

Material System	Nacelle Structure Revisions	Development Program Requirements	Producibility Risk	Recommendations
Organic Advanced Composite (Gr/Ep)	Moderate	Moderate	Moderate	Continue Design Effort
Metal Matrix Composite (B/Al)	Minor	Extensive	Very High	Stop Design Effort
Advanced Metallics (SPF/DB Titanium)	Minor	Moderate	Moderate	Continue Design Effort

<u>2.2.3 Preliminary Design</u>

The conceptual designs for the Organic Advanced Composite and the Advanced Metallic systems selected as best earlier in this section, have been refined to a preliminary design stage from which cost and weight analyses were made.

<u>2.2.3.1 Organic Advanced Composite Preliminary Design</u> - The conventional landing gear configuration was selected as the best concept and a preliminary design drawing has been made. Parts to be made from organic advanced composites using Gr/Ep include the shock strut cylinder assembly, the piston/fork assembly, the upper and lower torque links and the wheel.

All parts, except the wheel, will be fabricated by filament winding on a mandrel. The strut cylinder and the torque link parts will be fabricated, two at a time, on a metal mandrel and cut apart after cure. The piston/fork will be fabricated on an inflated mandrel which is a body of revolution and then after winding, the wet part will be placed in a mold and post formed to the offset fork configuration and cured.

The wheel is a mechanical assembly of two aluminum rim sections and two Gr/Ep wheel disks. The aluminum rim was selected because it is better for brake key attachment and heat dissipation. It also provides flat tire runout capability. The wheel disks are Gr/Ep composite laminations cut into pie shaped segments and laid up with staggered joints in a metal mold. Interleaved reinforcements are added to both the hub and the rim bolting area and on the inner wheel disk. The hub is reinforced with circumferential overwraping.

2.2.3.2 Advanced Metallic System Preliminary Design - The advanced metallic system, using SPF/DB titanium has been preliminary designed using the conventional landing gear configuration which was selected as best in the conceptual design study. Parts to be made using this process include the fork, the strut cylinder and the wheel. The fork, which consists of two side plates and four fittings, will be concurrently formed and diffusion bonded.

The strut cylinder walls are made as a truss core sandwich to provide an efficient section for axial and bending loads. It will be fabricated by loading the inner, the outer and the core sheets on a mandrel in a die with the trunnion lug fittings. The truss core and the outer sheet will be pressure formed out to the die cavity and diffusion bonded to the fittings.

The wheel consists of two halves which are mechanically assembled. Each half is an SPF/DB assembly which consists of the wheel disk, half of the wheel hub, the sealing ring and half of the rim. The wheel disks will be formed and diffusion bonded to the hub and the sealing ring in a die using the SPF/DB process.

2.2.4 Analysis and Evaluation

2.2.4.1 Total Landing Gear System Comparisons - The preliminary design drawing of the Organic Advanced Composite and the Advanced Metallic systems have been analyzed and evaluated to provide data for weight and cost comparison with the Baseline system. Structural Analysis, Producibility Evaluation, Installation Evaluation, Weight, Development Cost, Production Cost, Reliability, Accident Cost and Maintenance Cost analyses were made.

Structural analysis showed that the structural requirements of the landing gear can be met using either the Organic Advanced Composite or the Advanced Metallic material system.

The Producibility risk is rated as moderate for either material system, since landing gear parts have not been fabricated on a production basis using either material.

Installation of the Organic Advanced Composite landing gear requires a three-inch wider wheel well bay and a larger nacelle which will weigh 68.4 pounds more than the baseline. The Advanced Metallic gear requires only one inch extra and will only add 18.5 pounds to the baseline nacelle. This is because the ATS airplane is "volume limited" in the wheel well area and requires that the nacelle be increased in size to accommodate a largerlanding gear.

Weight calculations show that the Advanced Metallic system is lightest at 1104 pounds, the baseline concept weights 1164 pounds, and the Organic Advanced Composite system is heaviest at 1208 pounds. See figure 8.

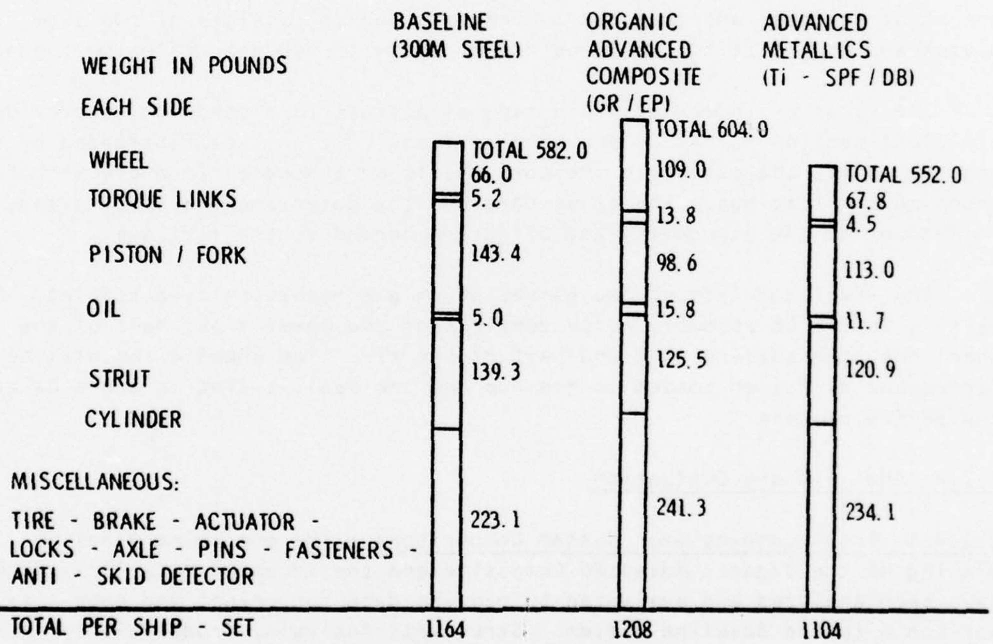


Figure 8. Weight Analysis - Comparison

Costs were obtained from two vendors for the Organic Advanced Composite components and since they were significantly different, they are presented as Vendor A and Vendor B costs.

Development costs are greater for advanced materials. Organic Advanced Composites costs from Vendor A are $988,040 over baseline development costs,

from Vendor B, $598,040 over and Advanced Metallics are $680,860 over the baseline development costs. See figure 9.

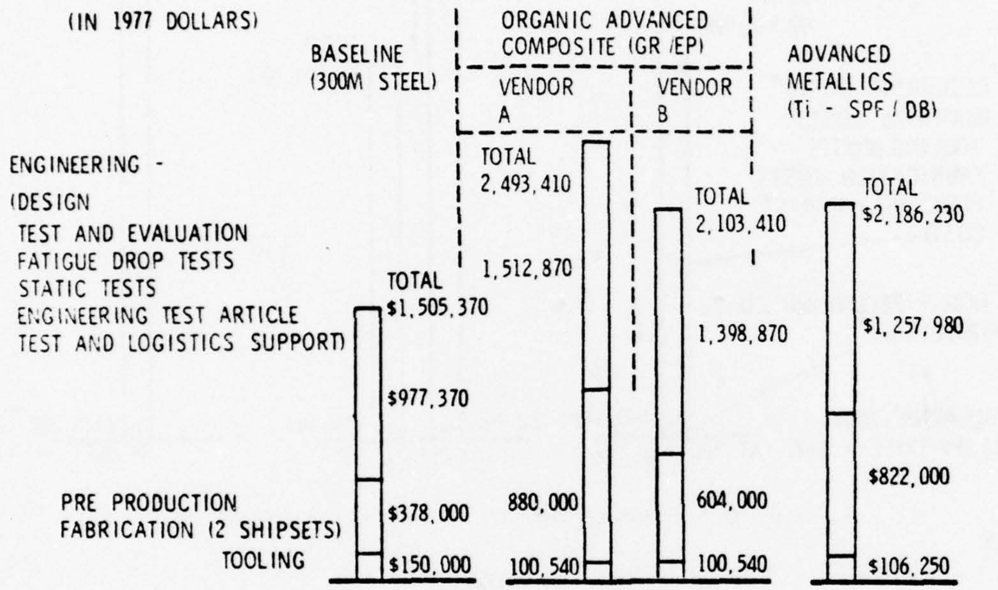


Figure 9. Development Cost Analysis - Comparison

Production costs were calculated using 500 units and an 85% cost reduction curve. The cumulative unit ship set average cost of the Organic Advanced Composite system from Vendor A is $104,254, from Vendor B is $72,926 and Advanced Metallic system is $93,664. Only the Vendor B Organic Advanced Composite system is less cost than the Baseline cost of $82,279. See figure 10.

The reliability of Advanced Material systems is better than the Baseline system. For the components that were redesigned to use Composites and Advanced Metallics, the MDR's were reduced 7% from the Baseline and the Condemnation Rates were reduced from the Baseline by 40% for the Composite and by 60% for the Advanced Metallic (Titanium).

The maintenance and support costs for the 10 year life span are $9,828,000 for the Baseline system, $178,000 more than baseline for Vendor A, Organic Advanced Composites, $213,000 less for Vendor B, and $382,000 less than baseline for the Advanced Metallic system.

A summary of the above evaluations is shown in table VI.

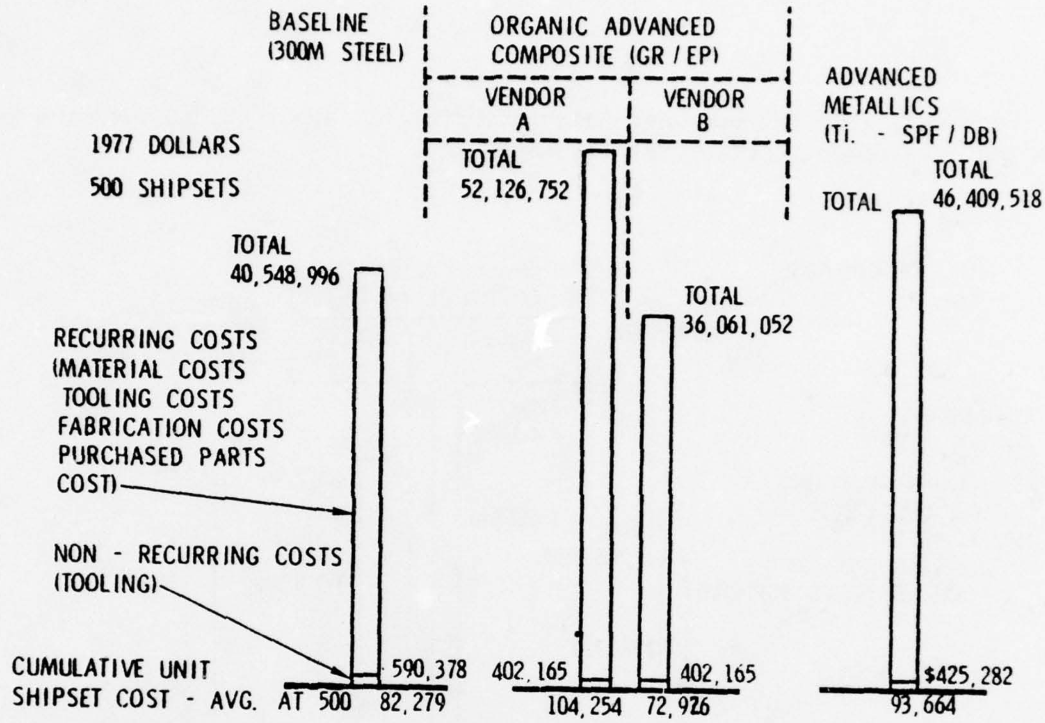


Figure 10. Production Cost Analysis - Comparison

TABLE VI

EVALUATION SUMMARY (NOT INCLUDING LIFE CYCLE COSTS)

PHASE II - ANALYSIS & EVALUATION

EVALUATION	BASELINE DESIGN (STEEL)	ORGANIC ADVANCED COMPOSITE SYSTEM	ADVANCED METALLIC SYSTEM
STRUCTURAL ANALYSIS	SATISFACTORY	SATISFACTORY	SATISFACTORY
PRODUCIBILITY EVALUATION	LOW RISK	MODERATE RISK	MODERATE RISK
INSTALLATION EVALUATION	BEST	68.4 POUNDS NACELLE WEIGHT ADDED	18.5 POUNDS NACELLE WEIGHT ADDED
WEIGHT	1,164 POUNDS LANDING GEAR	44 POUNDS Δ WEIGHT ADDED	60 POUNDS Δ WEIGHT SAVED
PRODUCTION COST	$82,279 SHIPSET UNIT AVERAGE COST	VENDOR A Δ +$21,975 COST ADDED VENDOR B Δ $9,353 LOWER COST	Δ +$11,285 COST ADDED
DEVELOPMENT COST	$1,505,370	VENDOR A Δ +$988,040 COST ADDED VENDOR B Δ +$598,040 COST ADDED	Δ +$680,860 COST ADDED
RELIABILITY ANALYSIS	GOOD MDR FAIR CONDEMNATION RATE	7% REDUCTION IN MDR 40% REDUCTION IN CONDEMNATION RATE	7% REDUCTION IN MDR 60% REDUCTION IN IN CONDEMNATION RATE
MAINTENANCE COST	$9,828,000	VENDOR A $178,000 COST ADDED VENDOR B $213,000 LOWER COST	$382,000 LOWER COST

BASELINE - LOWEST COST

ADVANCED METALLIC - LOWEST WEIGHT

An examination of this chart does not indicate which material system is best since the Organic Advanced Composite system from Vendor B is the lowest production cost, but the Advanced Metallic system is the lightest and has the lowest maintenance cost. A Life Cycle Cost analysis must be made before the most cost effective system can be determined.

2.2.4.2 Selected Best Component Comparisons - An evaluation has been made using selected components in an aircraft which is not "volume limited." If only the strut cylinder, the piston/fork, the hydraulic oil and the two torque links are examined, both advanced material systems show weight savings over the baseline. The Organic Advanced Composite parts save 39.2 pounds and the Advanced Metallic parts save 42.8 pounds when compared with the baseline.

Production costs for this selected group of parts are higher for advanced materials, but since the weights are lower, the "effective cost" would change when the "cost of weight" is used to reduce the cost of the parts. On the ATS aircraft, this cost is $431 per pound of Weight. See figure 11.

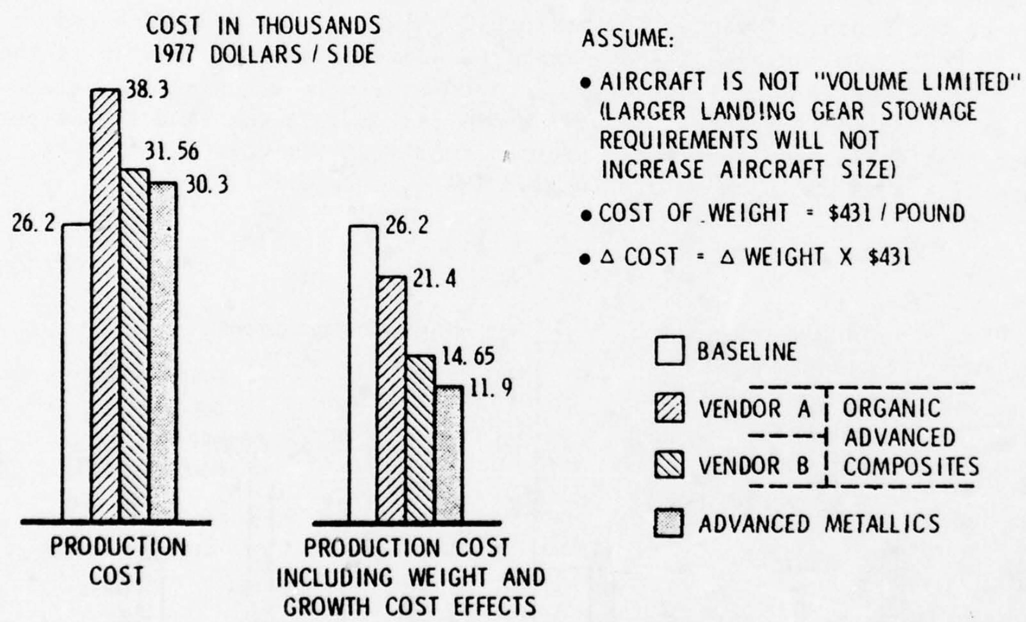


Figure 11. Selected Best Components - Cost Comparison

This chart shows that the weight cost effect has reversed the cost picture so that the Organic Advanced Composite parts from Vendor A cost $4800 less, from Vendor B, $11,550 less, and the Advanced Metallic parts cost $14,300 less than the baseline cost for these selected parts.

2.2.5 Life Cycle Costs

A Life Cycle Cost Analysis of both material systems has been made. These costs include development, production, support, accident cost and fuel costs. In these calculations the change in LCC due to weight changes was calculated and added to the other direct costs. The fuel costs were a change to the Organic Advanced Composite system LCC by an added $2,484,000, while fuel cost savings reduced the LCC of the Advanced Metallic system by $917,200.

Accident costs, resulting from stress corrosion related failures, totaling $18,105,000 were added to Baseline LCC and $5,974,000 were added to the Advanced Metallic (Titanium) LCC. This lower cost is due to the corrosion resistance of titanium. Composite material is corrosion free, so no cost was added.

The total Life Cycle Cost for the Advanced Metallic system (SPF/DB titanium) is $22,886,000 under the baseline LCC, while Organic Advanced Composite, Vendor A, is $39,815,000 over and Vendor B is $22,968,000 over the baseline LCC. Figure 12 shows that the weight and growth factors have added to the Organic Advanced Composite LCC while reducing the Advanced Metallic LCC. This analysis shows that the Advanced Metallic system is the most cost effective material system for the ATS airplane, which is "volume limited." Another airplane "not volume limited," would not have the weight impact of the ATS nacelle growth, and may show that the Organic Advanced Composite system could be more effective than the Baseline.

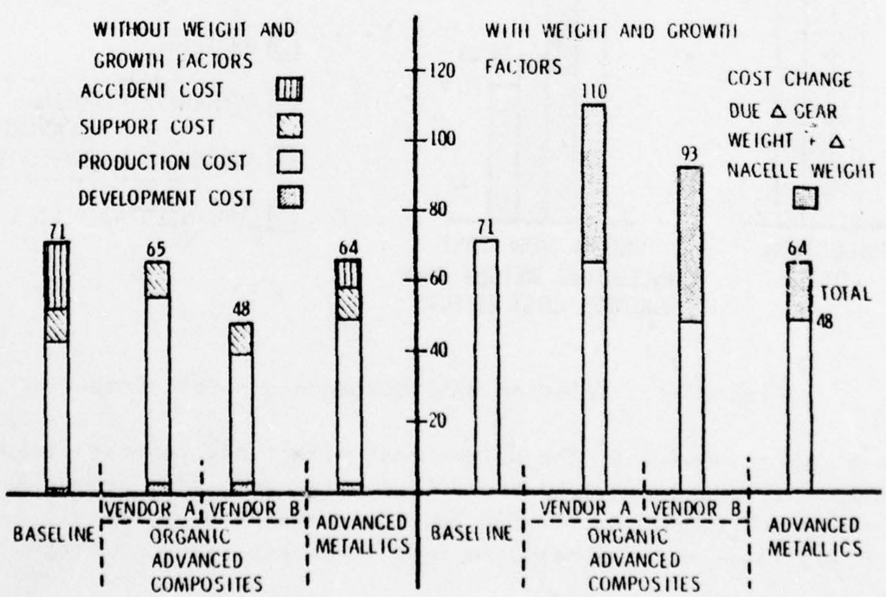


Figure 12. Life Cycle Costs Comparison Chart (Millions of 1977 Dollars)

SECTION III

BASELINE

The landing gear systems used as baselines for this study were the B-1 nose landing gear for the Phase I section and the ATS advanced fighter main landing gear for the Phase II section of this program. The contractual change in the Phase II section of the program specified that the proposed landing gear for the ATS program be used as a baseline.

3.1 PHASE I BASELINE

The B-1 nose landing gear has twin wheels and tires on a semicantilevered strut with a folding drag brace. A jury strut downlock holds the drag brace in the on-center position when the gear is in the extended and locked position. The shock strut is a dual chambered air-oil piston type.

This nose gear meets all the requirements for the B-1 airplane and complies with MIL-A-8862. The dimensional constraints, hardware dimensions, drawings, external loads, component loads, weight estimates, environmental data, reliability, maintainability, cost and life cycle estimates were obtained from the B-1 program and are presented in Appendix A, the Phase I report.

3.2 Phase II BASELINE

The Phase II baseline landing gear information has been obtained from a separate Rockwell ATS study program. The ATS advanced fighter configuration used as a baseline is shown in figure 5. The operational requirements for this aircraft are:

10 year life
500 aircraft total
20 wings
25 aircraft per wing
25 flying hours per month
150 sorties per month, per wing

The tricycle type landing gear configuration consists of a nose gear and two main landing gear assemblies which have been designed as an optimum gear which is compatible with the above configured airframe structural design for a 53,000 pound gross weight air vehicle. This is a conventionally

configured main landing gear and uses "state-of-the-art" metallic materials. It consists of two single wheel assemblies mounted in the engine nacelles. The gear assembly is fully retractable to the aft using a hydraulic actuator with power from the airplane hydraulic system. When fully retracted, the gear is completely contained within the airplane contour.

The data presented in this section completely describes all the design parameters and constraints used in the design of the ATS advanced fighter main landing gear.

3.2.1 Design Requirements

The ATS main landing gear has been designed to comply with the landing and ground handling requirements of MIL-A-8862. Since it is readily available, this specification has not been included with this report.

The ATS main landing gear must meet the following design requirements characteristics.

3.2.1.1 Performance. The performance of the landing gear system shall permit required ATS performance for landing, takeoff and flotation, and shall provide the following functions:

1. Absorb and/or transmit the static and dynamic energy resulting from the air vehicle takeoff, landing, and ground manuevering operations.

2. Provide directional control to accomplish steering, turning, pivoting, taxiing, and braking of the air vehicle.

3. Provide ground flotation for the air vehicle during ground maneuvers.

4. Provide for retraction, extension, and locking of the main and nose gears for the flight and ground mode of operation, and provide indication and warning to the pilot of gear position.

5. Provide for towing, tie-down and wheel jacking.

3.2.1.2 Landing Gear Operation. The main and nose landing gear assemblies shall be hydraulically operated and electrically controlled. Gear position shall be selected by means of the landing gear control handle located in the flight station. Sequencing shall be accomplished by use of switches,

relays, solenoid and/or mechanically operated valves. Protection against inadvertent retraction of the landing gear with the air vehicle on the ground shall be provided.

The main and nose landing gears shall be fully retractable and completely enclosed when in the retracted position. The gears shall automatically lock in the extended and retracted position by means of positive mechanical locks. Locking the gears in either the extended or retraced position shall not be dependent upon hydraulic pressure. The locks shall be designed such that they shall release the gears prior to or at the same instant the gear extension actuator receives hydraulic pressure. The main gear doors and gear uplock mechanisms shall be unlocked by hydraulic power. Fairings and closures shall be designed with adequate clearance considering flat tire, flat strut conditions, tire growth and installation misalignment. Interruption of the control sequence or driving power to the landing gear and fairing door actuation system during normal or emergency operation shall not result in system malfunction or structural damage to any part of the air vehicle. The landing gear and fairing doors shall continue to the selected position upon reapplication of hyraulic power.

Retracting and extension time for the main landing gear and door assemblies shall be as shown in table VII. The main landing gears shall be retracted and locked before the air vehicle reaches 75 percent of the gear structural design limit speed (V_{LF}) at the maximum rate of acceleration.

TABLE VII

RETRACTION AND EXTENSION TIME

Item	Temperature	Minimum Allowable Time to Open Doors And Extend And Lock Gears	Maximum Allowable Time to Retract And Lock Gears And Doors
a.	Above minus 20° F	15 seconds	15 seconds
b.	Minus 65° F to minus 20° F	30 seconds	30 seconds

Emergency extension time shall not be greater than 2 times the maximum allowable operating times specified above.

The main landing gears shall be designed to withstand air loads resulting from speeds up to 300 knots equivalent air speeds (EAS) for all extension positions to full extension, and shall be capable of operating (retraction and extension) at speeds up to 250 knots EAS. Actuators and linkages shall be designed to withstand the loads imposed by these design operating conditions, including the effects of hydraulic surges and pressures.

An emergency extension control shall be provided that is independent of the normal gear operating controls. It shall be possible to extend the landing gear to the down and locked position in the event of any single hydraulic or electrical component failure. The landing gear shall be capable of emergency extension to a down and locked position independent of the air vehicle hydraulic and electrical power generation subsystems. Primary means of emergency operating power shall not be dependent upon battery power. Emergency extension time shall be not greater than twice the maximum allowable operating limits specified in table VII.

Provisions for jacking and towing shall be incorporated in accordance with MIL-STD-809 and MIL-STD-805.

3.2.1.3 Reliability. The landing gear system shall incorporate those design characteristics essential to the achievement of the quantitative and qualitative reliability requirements specified for the air vehicle.

3.2.1.4 Maintainability. The landing gear system shall incorporate those design characteristics essential to the achievement of the quantitative maintainability requirements specified for the air vehicle.

The standard Air Force policy of three levels of maintenance (organizational, intermediate, and depot) shall be employed for the landing gear systems. The following qualitative requirements shall apply.

The landing gear system shall be self-sufficient to the extent of permitting preflight inspections to be performed without prepositioned AGE, and permitting postflight inspections to be performed without prepositioned AGE, except for step ladders or workstands, and ground safety locks/devices

The landing gear system shall permit all maintenance to be accomplished by Air Force technicians five-skill level maintenance personnel, with occasional seven-skill level personnel, using existing Air Force facilities and, for most tasks, existing AGE. Design for repair by Air Force technician three-skill level maintenance personnel shall be a goal.

Equipment design shall reflect thorough consideration of the capabilities of human resources available to maintain the equipment and the utilization of automatic test equipment to support maintenance personnel.

3.2.1.5 Major Component Characteristics. The main and nose landing gear shock struts shall comply with the requirements of MIL-L-8552, MIL-T-6053 and AFSC DH 2-1. The shock struts shall be designed such that the passage of oil through an orifice shall absorb the energy of impact and in which dry nitrogen is used as the elastic medium to restore the unsprung parts to their extended position. The shock struts shall be capable of withstanding the loads derived from MIL-A-8860, MIL-A-8862, MIL-A-8866, MIL-A-8867, including static strength and four lifetime fatigue requirements. The air vehicle design sinking speed shall be 10 feet per second at the landplane landing design weight and 6 feet per second at the maximum design landing weight. The shock struts shall be capable of supporting the air vehicle on a flat strut (loss of nitrogen) through the complete landing cycle, at normal landing conditions, without damage to the shock struts or carry-through structure. A complete landing cycle at normal landing conditions shall consist of landing at a landplane landing design weight at a sink speed of 6 feet per second. The landing runout and taxi design load for the flat strut condition shall be the static gear load at maximum taxi weight times a dynamic factor of 1.2. Compression ratios shall be compatible with all applicable landing gear system performance requirements. The shock strut shall have a design vertical stroke of 12 inches measured at the axle centerline and a design 4 inch stroke from static to compressed position. The torsional spring rate, in the static position, shall not exceed 1.4×10^{-4} radians per 1000 inch/pounds.

The main landing gear wheel assemblies shall comply with the requirements specified in MIL-W-5013, except the wheels shall be capable of being rolled a distance of 2500 miles, including consideration for combined radial and side loads corresponding to those produced by 0.25G turns. A pressure relief valve shall be provided for the wheel to prevent overpressurization of the wheel and tire assembly. Provisions for a tire change counter shall be incorporated in each wheel for recording a minimum of 50 tire changes. A tire pressure gage shall be incorporated on the outboard side of the wheel assembly. The gage shall conform to MIL-G-83016, except the gage shall withstand exposure to vibration and to a burst pressure of the tire.

3.2.1.6 Dimensional Constraints. The dimensional constraints for the ATS main landing gear are shown in figure 5, the air vehicle configuration drawing, and figure 6, the baseline main landing gear drawing.

3.2.1.7 Metallic Hardware Dimensions. Dimensions of the ATS main landing gear hardware are shown in figure 6, the baseline main landing gear drawing.

3.2.2 Baseline Main Landing Gear Description

The ATS main landing gear assembly consists of a semicantilevered shock strut with a single tire and wheel mounted in the engine nacelle. The forward nacelle engine air intake section has a split duct with a faired center island which extends from the inlet back to the engine compartment. The main landing gear is housed within this center island of the nacelle. The gear assembly is fully retractable aft, and is completely contained within the airplane contour when retracted. A hydraulic actuator, using air vehicle hydraulic power, is used to extend and retract the landing gear.

The landing gear assembly is attached to the nacelle structure by journaled trunnions at the lower end of the strut main body and latched into extended and retracted positions by a locking device at the top of the strut. The trunnions are supported by nacelle frames which are fastened to the front spar of the wing.

With the gear locked in the extended position, the vertical and side loads are reacted at the trunnions and the drag loads reacted by the trunnions and the upper latch. The torsional loads on the gear are reacted by the torque links which are fastened to the fork (piston) and the strut body. These links hinge to allow the fork vertical motion, but resist the torsion loads between the fork and the strut body.

The strut shock absorber will be an air-oil type in which the passage of metered oil through an orifice is used to absorb landing impact energy and to control the rate of compression. A snubber valve controls the rate of extension of the piston. The shock strut will support the airplane weight on the elastic medium of nitrogen and hydraulic fluid which will cushion and absorb the taxiing loads and will restore the gear to the extended position when unloaded.

The strut (outer cylinder) and fork (piston) will be fabricated from 300M steel, heat treated to 280-300 ksi. The strut consists of a machined cylinder and end caps. The upper cap contains the latching device which has a bungee to hold the pin in position if the hydraulic pressure is reduced. The fork (piston) is a machined part with an upper cylinder (piston) and a lower angled cylinder (fork) section. The lower cylinder is then hot formed to the fork configuration. An axle socket is welded to the lower end of the fork to complete the part. The axle socket has a jack pad on the

bottom which will allow jacking of the air vehicle at gross weight. The axle is a machined 300M steel cylinder which is pressed into the axle socket. The metering pin is a machined aluminum part which fits into the upper hollow interior of the piston section of the fork. The upper aluminum bronze bearing is positioned against the upper flange of the piston and held by the cylindrical aluminum spacer which is pinned to the piston. This spacer limits the stroke of the piston.

The orifice and orifice support tube are assembled and placed into the upper end of the strut. The upper cap is then screwed onto the strut and the orifice support tube is held between the strut and the cap.

Assembly of the fork and strut consists of inserting the piston section of the fork into the strut between the orifice and the outer strut wall. The lower aluminum bronze bushing is positioned into the lower end of the strut and held in place by a retainer nut. This lower bushing provides the piston stroke limiting stop for the upper piston spacer.

Torque links, which keep the wheel aligned, are made of 7075-T736 aluminum and are bolted together at the apex and to the lugs on the fork. The upper torque link is assembled onto the main trunnion pin between the lugs on the strut.

Airframe trunnions have self-aligning bearings for the trunnion pin. Installation of the strut into the wheel well is accomplished by positioning the strut and inserting the trunnion pin through the airframe trunnion bearings, the strut lugs, spacer tube and upper torque arm lugs. Retainers are then placed into the ends of the hollow trunnion pin and held in position by a through bolt.

Wheels will be 34 x 9.9 x 14.5 size and will be made from two 2014-T6 aluminum forged wheel sections. Wheel assembly will include the tire, two wheel sections, which are bolted together, wheel bearings and the cylindrical false axle. Installation of the wheel assembly consists of slipping the false axle over the structural axle and screwing the retainer nut onto the axle. The brakes will be contained within the 14.5 inch diameter wheel. The wheel brake section will be keyed to the inner wheel section rim and the stationary brake is mounted to two lugs on the fork. Brake operating power will be provided by two individual hydraulic sources. One pressure source will provide the required wheel braking torque with the second system as an emergency backup.

3.2.3 External Loads

The external loads acting on the baseline (300M steel) main landing gear of the ATS advanced fighter were obtained from a study of the ATS which

generated loads using a computer program entitled "Structural Weight Estimation Program," known as "SWEEP."

SWEEP is a computer program with major engineering analysis modules structured around preliminary design procedures and integrated into a working program that can completely analyze structure weights and mass properties of major vehicle components.

The basis for the structural weight analysis in SWEEP is an approximation of the procedures and methods used in the actual structural analysis and design processes through the creation of an engineering description of the components in terms of physical geometries, design criteria, structural sizings and mass properties. This is accomplished through mathematical modeling procedures and the adaptation of theoretical, empirical, and/or statistical methods to a logical but flexible, interrelated computational procedure. The structural sizes are synthesized from design requirements and criteria data developed from evaluation of configuration design criteria by special analysis routines. The load analysis in the landing gear subroutine of SWEEP follows the procedure outlined in MIL-A-8862A.

The takeoff and landing conditions for the ATS are defined in table VIII. Additionally, based on the aforementioned SWEEP program, external main gear loads were generated for eight critical design conditions. These generated loads are summarized in table IX, which also describes appropriate load application points, as well as appropriate strut extension length data. It should be noted that the load denoted as "UP" is meant to mean along the strut/piston axis, while "AFT" or "INBOARD" are orthogonal to the strut axis and each other. Location of external load application points are also shown in figure 13, which also shows schematically the general location of the various components of the main gear assembly. The "schematic" is a typical configuration for all gear concepts (300M steel baseline, SPF/DB titanium, and graphite/epoxy composite) investigated under this study. For the purposes of analysis, all of the aforementioned design loads were considered to occur in a room temperature environment (70°F).

TABLE VIII

ATS TAKEOFF AND LANDING CONDITIONS

Condition	Weight (lbs)	Load Factor	Landing Speed Ft/Sec.	Sink Speed Ft/Sec.
Takeoff	53,000	1.629	253.2	6.00
Landing	47,400	2.743	202.5	10.00

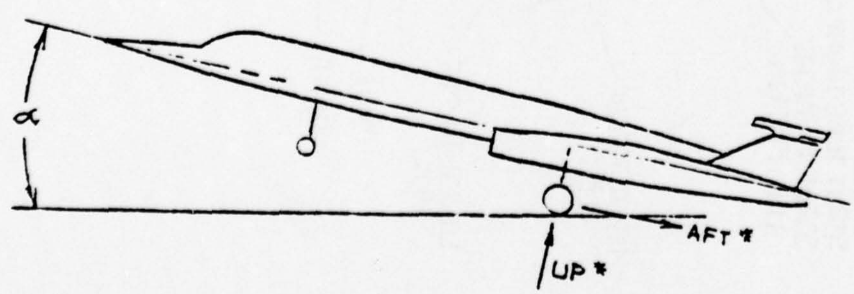
TABLE IX

SUMMARY OF
MAIN LANDING GEAR EXTERNAL LOADS

Condition No.	Condition Description	(1) Strut Position	Load (2) Application Point	(1) Load Direction	Limit Loads (lbs) Takeoff Value	Limit Loads (lbs) Landing Value
1	Two Point	A	C	UP AFT	25020 6254	62156 15538
2	Spin-Up	A	C	UP AFT	21783 16773	42653 32847
3	Spring Back	A	C	UP FORWARD	25020 14976	62156 29327
4	Braked Roll	B	D	UP AFT	39750 31800	42660 34128
5	Drift	A	D	UP INBOARD	12510 10008	31078 24862
6	Unsymmetric Braking	B	D	UP AFT	32095 25676	28704 22963
7	Towing	B	C	UP + AFT	35715 12343	
8	Turning	B	D	UP INBOARD	64381 32190	

(1) Strut Position: A = 2 inches from fully extended
B = 8 inches from fully extended (Static)

(2) Refer to Figure (1) for location of load application point
C = at centerline of axle
D = at ground at tire contact point



* Analysis Coordinates

α = 0° for all conditions except No. 1 forward α = 12.5°

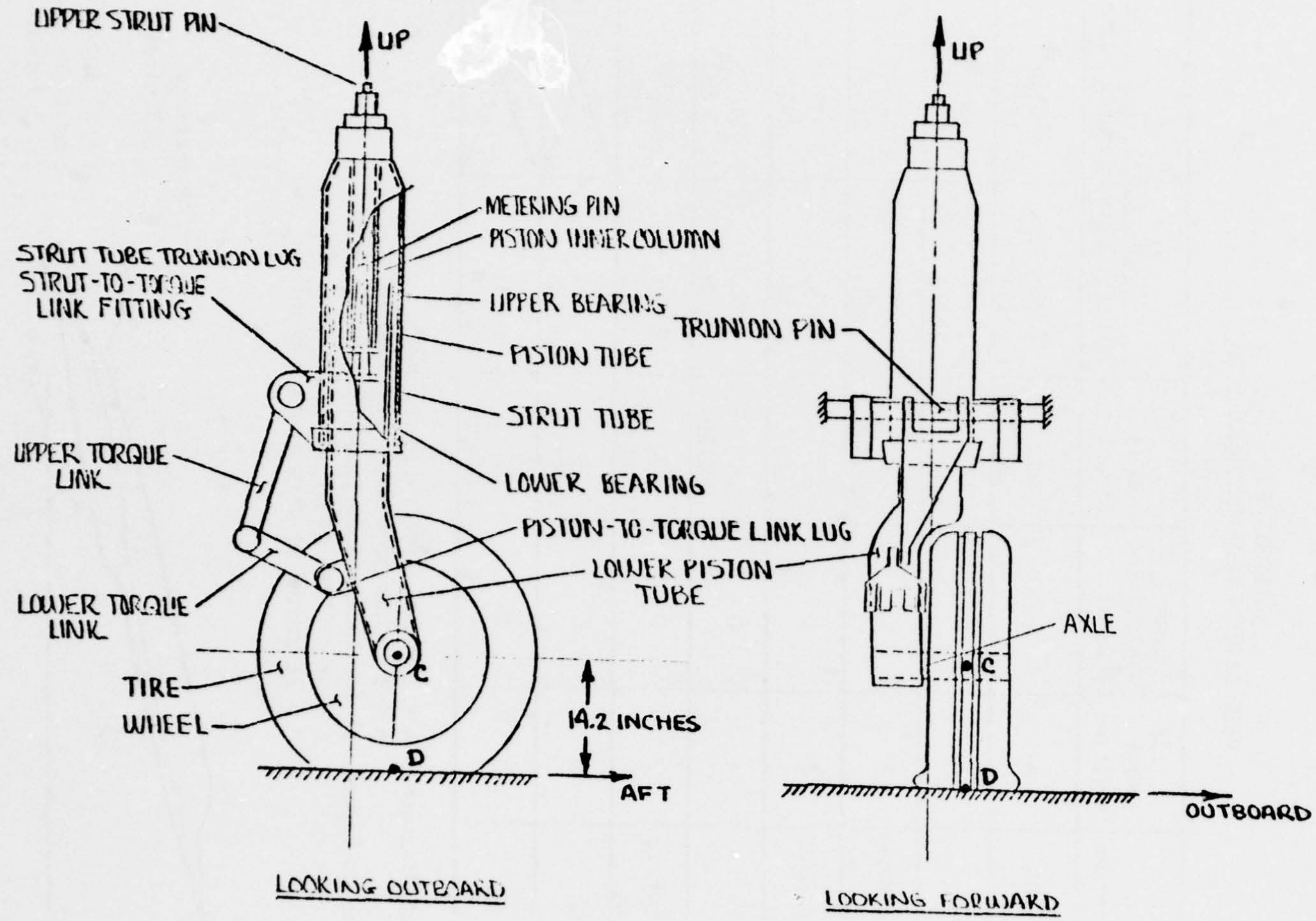


Figure 13. Schematic of Typical Landing Gear Assembly and Location of Components

3.2.4 Component Loads

The external loads, as previously discussed, were used to obtain component loads as described in this section. First, the appropriate deflection (fore or aft, inboard or outboard) of the axle-to-lower piston tube attach point (point C on figure 13) was "estimated" or calculated using the lower piston tube section and material properties. Then, using the deflected geometry dimensions, loads were determined by finding the various reactions within the gear structure due to the external loads. These reactions were determined for all conditions for the 300M steel baseline gear configuration. Reactions calculated included the following:

Upper and Lower Bearing Reactions (X, Y)

Torque about the Piston/Strut Tube Axis (M_{zz})

Upper Strut Pin Reaction (X)

Trunnion Pin to Strut Tube Fitting Reactions (X, Y, Z)

where + X is AFT

+ Y is OUTBOARD

+ Z is UP

3.2.5 Stress Analysis

The 300M steel baseline main landing gear components (see figure 13) were analyzed using standard analysis methods to determine working stress levels at various critical sections of the components and combined loading margins of safety were determined for all components based on the 300M steel material properties per table X. Load factors employed in the analysis were as follows:

LIMIT LOAD = 1.0
ULTIMATE LOAD = 1.5
FITTING FACTOR = 1.15

For the sake of brevity, no detailed discussion of the analysis will be presented. A summary of critical (minimum) margins of safety for each component of the 300M steel gear concept is presented as table XI. Refer to figure 13 for component locations. No negative margins of safety were determined by this analysis, hence, the 300M steel gear concept (per figure 6) is considered structurally adequate for the previously defined design loads.

TABLE X

BASIC MATERIAL PROPERTIES

300M STEEL

275,000 - 305,000 psi HT

Room Temperature

F_{tu} (L and T)	275,000 psi
F_{t_y} (L and T)	227,000 psi
F_{c_y} (L and T)	252,000 psi
F_{s_u}	157,000 psi
F_{br_u}	462,000 psi
F_{br_y}	362,000 psi
E_t	29×10^6 psi
E_c	29×10^6 psi
G	11×10^6 psi
F_{tp}	190,000 psi

TABLE XI

SUMMARY OF MINIMUM MARGINS OF SAFETY - 300M STEEL BASELINE GEAR

GEAR COMPONENT	CRITICAL CONDITION	TYPE OF (1) LOADING	MINIMUM MARGIN OF SAFETY (M.S.)	APPENDIX II REFERENCE PAGE
Piston Tube				
At Upper Bearing	4	S	+ 1.96	II-A-57
4.5" Below Upper Bearing	2	S+B	+ 0.117	II-A-58
At Lower Bearing	8	S+B+HT	+ 0.26	II-A-58
Lower Piston Tube	4	S+B+A+TR	+ 0.070	II-A-73
Piston-To-Torque Link Lug	8	SO	+ 1.80	II-A-77
Upper Strut Pin	4	S+B	+ 0.13	II-A-78
Strut Tube				
At Upper Bearing	2	A+B+S	+ 0.29	II-A-81
At Lower Bearing	8	Z+B+S	+ 0.06	II-A-91
Strut Tube Trunnion Lug	8	SO	+ 0.37	II-A-95
Axle	4	S+B+TR	+ 0.034	II-A-93
Upper Torque Link				
Link Web	2	S	+ 0.998	II-A-105
Link Cap	2	A	+ 1.258	II-A-105
End Lug	2	SO	+ 0.15	II-A-107
Lower Torque Link				
Link Web	2	S	+ 0.998	II-A-109
Link Cap	2	A	+ 1.258	II-A-109
End Lug	2	SD	+ 0.05	II-A-106
Trunnion Pin	8	S+B	+ 0.06	II-A-121
Bearings				
Upper	2	BR	+ 0.012	II-A-126
Lower	4	BR	+ 0.005	II-A-127
Piston Inner Column	8	Col. Stability	+ 0.22	II-A-131
Actuator Cylinder	-	HT-M	+ 0.06	II-A-133
Wheel				

(1) LOADING CODE: B = Bending Stress, A = Axial Stress, S = Shear Stress, HT = Hoop Stress, BR = Bearing Stress, SO = Shearout Stress, TR = Torsional Stress, M = Meridional Stress

3.2.6 Weight

The total weight of the ATS main landing gear baseline is calculated to be 1164 pounds, as is broken down in Table XII.

TABLE XII

WEIGHT BREAKDOWN

ATS MAIN LANDING GEAR BASELINE

Description	Wt. Per Side (Pounds)
Strut (outer Cylinder)	139.30
Fork and Piston (inner strut cylinder)	143.40
Axle	9.11
Torque Links (upper and lower) (Aluminum)	5.20
Gear Locks (up and down)	19.64
Actuator Cylinder	7.38
Wheels (Aluminum)	66.00
Tires and Brakes	166.50
Misc. (oil, air, anti-skid dectector)	25.50
Weight Total	582.00

ATS Main Landing Gear System - Weight Total 1164.00 PER AIR/VEHICLE

3.2.7 Environmental Data

The landing gear shall be capable of operation in conditions as defined below:

Temperature	-65 to +120°F
Pressure	10.1 to 15.4 psi
Humidity	0 to 182 grains H_2O/lb. dry air
Rain	Operational world wide precipitation extremes
Salt Fog and Spray	Salt particle size 1.0 micron diameter minimum
Sand and Dust	Dust size .1 to 10 microns in dia. Sand size 10 to 1000 microns in dia. Concentration up to .5 gram/ft.^{3} air

3.2.8 Development Cost

Development or implementation costs include such nonrecurring costs as Engineering hours for design, system and program management, tests and evaluation. Preproduction tooling costs and prototype and test article fabrication costs are also included. These cost estimates were developed parametrically from data generated by other programs. See table XIII for Development Costs.

3.2.9 Production Cost

The cost estimate for the ATS main landing gear was developed from several sources of data. Material costs per pound and hours per pound fabrication costs were obtained from B-1 landing gear data. The wheels, tires, brakes and anti-skid device costs were taken from recent quotes for the Rockwell -65 Sabreliner program. These costs were adjusted for differences in weights.

The learning curve used for fabrication was 89% and was based on vendor data. Assuming one release for the 500 units, the true midpoint for the fabrication effort is unit 169.73. Adding the materials cost and the prorated recurring costs of the tooling to the fabrication costs produces a cost reduction curve of 92%, see figure 14. See table XIV for results of the cost analysis.

TABLE XIII

BASELINE DEVELOPMENT COSTS

(RDT&E costs in thousands of 1977 dollars)

Engineering		
Design	$	393.04
Test and Evaluation		275.13
Fatigue Drop Tests		107.00
Static Tests		82.00
Engineering Test Articles		82.00
Test and Logistics Support		38.20
Subtotal	$	977.37
Preproduction		
Fabrication of 2 Shipsets	$	378.00
Tooling		
Labor and Materials		150.00
Total	$	1,505.37

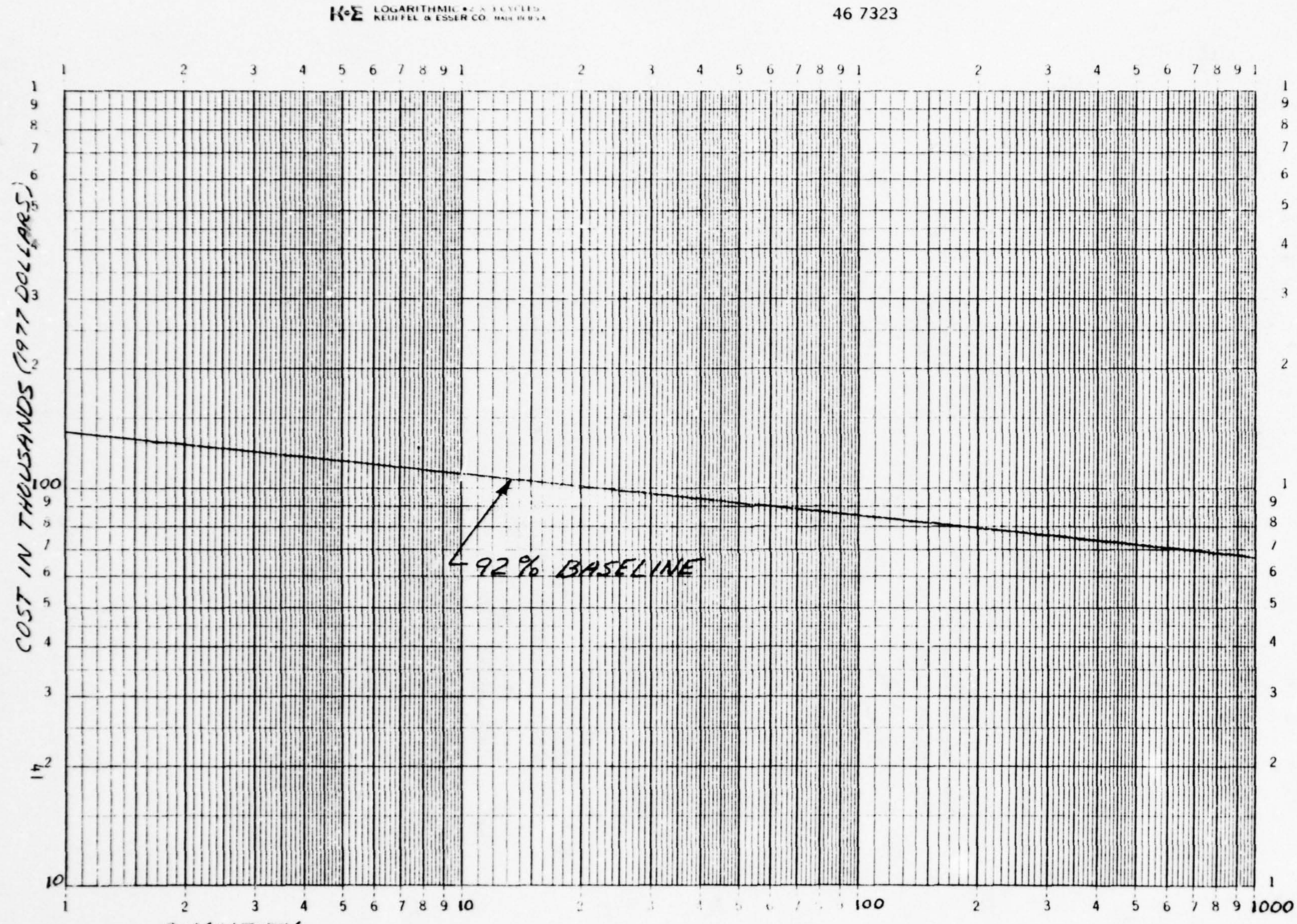


Figure 14 . Landing Gear Study
Production Cost Per Shipset

14

TABLE XIV

PRODUCTION COST - BASELINE
(1977 Dollars)
500 Shipsets

Nonrecurring Costs	
Tooling hours	(19,418)
Tooling dollars	$ 544,400
Tooling material	$ 45,978
TOTAL	$ 590,378
Recurring Costs	
Fabrication hours	(755,729)
Fabrication dollars	$ 22,626,526
Production material	$ 13,816,634
Tooling hours	(19,699)
Tooling dollars	$ 541,134
Tooling material	$ 45,702
Tires; brakes antiskid detector	$ 3,519,000
TOTAL RECURRING COSTS	$ 40,548,996
CUMULATIVE UNIT SHIPSET COST - AVERAGE AT 500 SHIPSETS	$ 82,279

Total nonrecurring tooling cost will be $590,378 and total recurring fabrication and material costs will be $40,548,996. The total production cost for 500 units will be $41,139,374 with a cumulative unit average at 500 of $82,279.

3.2.10 Reliability

The two reliability factors that were determined for the baseline ATS main landing gear were the corrective "Maintenance Demand Rates" (MDR) and the condemnation rates. The condemnation rate is the product of the MDR times a condemnation factor.

The condemnation factor is a variable which measures the amount of repair possible before the equipment must be condemned and discarded. The condemnation factors were established using data from previous experience with similar equipment and factors being used by Air Force Logistics Centers in the K051 system.

The Condemnation Rates were determined using vendor data and AFM66-1 data for various aircraft and are presented in Table XV.

The total corrective MDR for the baseline landing gear is 24,329 per 10^6 flight hours. Tires and brakes make up 95% of this total and are the highest individual MDR and also the highest condemnation rates.

3.2.11 Maintainability

The maintenance and logistics support costs for the fleet of 500 aircraft over a life span of 10 years will be $6,151,000 spares cost and $3,676,800 personnel cost.

The baseline preliminary design drawing was evaluated to define the maintenance required. This study established maintenance tasks, task times, personnel required, maintenance demand rate (MDR), and group support equipment required. This was done by performing an on-aircraft and off-aircraft analysis on each line replaceable unit (LRU) such that the following information is generated and tabulated.

A. Maintenance task or activity

B. Task time duration (estimated or timelined)

C. Maintenance demand rate (MDR) for each task

D. Personnel required (quantity) per task

TABLE XV

CORRECTIVE MAINTENANCE DEMAND RATES AND CONDEMNATION RATES

MAIN LANDING GEAR - METALLIC BASELINE

WUC NUMBER	NOMEMCLATURE	MDR X10^6	PERCENT CONTRIB	CUM PERCENT	RANK	VENDOR OR AFM66-1 DATA SOURCE	CONDEMNATION RATE X10^6
13CDA93	Tire	20000.0	82.2	82.2	1	*	2600.0
13FAC	Brake Stack Assembly	1550.4	6.4	88.6	2	Goodyear Tire & Rubber	77.5
13FBF	Brack Actuator Assembly	1550.4	6.4	95.0	3	Goodyear Tire & Rubber	77.5
13CBL	Strut Hyd. Actuator	296.6	1.2	96.2	4	B52, F-4C, KC-135	14.8
13BAA9a	MLG Cylinder	270.0	1.1	97.3	5	B-58, C-141, KC-135	27.0
13CDA9*	Wheel Assembly	250.0	1.0	98.3	6	Goodyear Tire & Rubber	12.5
13BAC1	Downlock Assembly	165.0	0.7	99.0	7	T-39	8.3
13BAC2	Uplock Assembly	165.0	0.7	99.7	8	T-39	8.3
13BAQ1	Torque Link-Upper	22.0	0.1	99.8	9	Cleveland Pneumatic	1.1
13BAQ2	Torque Link-Lower	22.0	0.1	99.9	10	Cleveland Pneumatic	1.1
13BAA9B	MLG Piston	14.0	0.1	100.0	11	B-58, C-141, KC-135	0.1
13GCB	Anti-Skid Detector	13.6	0.0	100.0	12	Crane Hydro-Aire Div.	13.6
13BAA9C	Axle	10.0	0.0	100.0	13	B-58, C-141, KC-135	0.5

TOTAL MDR = 24,329 per 10^6 flight hours
TOTAL MTBCMA = 41.1

* Based on tire failure plus wear which requires that tires be replaced or retreaded every 100 flight hours.

NOTES:

WUC NUMBER	Work Unit Code Number
NOMENCLATURE	Description of Components
MTBCMA	Mean Time Between Corrective Maintenance Action
MTBCMA	1.0/Maintenance Demand Rate
MDR	Corrective Maintenance Demand Rate (Per 10^6 Flight Hours)
CONDEMNATION RATE	Condemnation Factor X Maintenance Demand Rate
PERCENT CONTRIB.	Percent Contribution of the Individual WUC (Component) to the Total Subsystem MDR
CUM PERCENT	Cummulative Percent Contribution of the WUC's (Components)
RANK	WUC's (Components) are ranked by Percent Contribution of the Total Subsystem MTBCMA

E. Required ground support equipment per task (brief description of equipment)

F. LRU quality per aircraft

Support requirements are derived as follows:

A. "Maintenance Tasks" are those maintenance actions associated with the system or LRU which require corrective action when the item fails or requires servicing (e.g., preflight inspection, tire remove or replace, etc.).

B. "Task Time Duration" is the estimated time required to accomplish the task.

C. "Maintenance Demand Rate" is the rate at which the maintenance action will occur during the life of the aircraft.

D. "Personnel Required" is the number of personnel required to perform the task.

E. "Required Ground Support Equipment" is a brief technical description of the ground support equipment required to accomplish the task (e.g., hydraulic cart, stand, calibration unit, etc.).

F. "LRU Quantity" is the quantity of like LRU's on the aircraft.

Maintenance actions and associated resources were identified for the following general categories:

Preflight inspection
Postflight inspection
Scheduled inspection
Servicing operations
On-aircraft corrective maintenance
Off-aircraft corrective maintenance

The servicing and inspections, maintenance is shown in table XVI. A summary of MDR data which resulted from this analysis is shown in table XVII and the detailed data is presented in Appendix E, and includes table E-I, On-Aircraft Corrective Maintenance and table E-II, Off-Aircraft Corrective Maintenance. Operational support equipment for both on-aircraft and off-aircraft is summarized in table XVIII and XIX respectively.

TABLE XVI

SERVICING AND INSPECTIONS MAINTENANCE

LRU WUC NO.	LRU NOMENCLATURE	QTY PER A/C	MDR PER 1000 FH	MAINTENANCE TASK DESCRIPTION	TASK TIME (MINS)	MAINTENANCE SUPPORT RESOURCES			
						CSE (I.D.)	PERSONNEL		OTHER (SPECIFY)
							AFSC	QTY.	
13***	Landing Gear Assy (2)	2	250	PREFLIGHT Visual Inspection Leaks & Loose 02 Broken Hardware MLG Press. Position	3 Min.	None	43151	1	
			250	POSTFLIGHT Leaks Broken Hardware Brakes MLG Press. Position	3 Min.	None	43151	1	
			6.5	SERVICING Service GN_2 MLG Strut (2 Assy)	60 Min.	GN_2 Servicing Cart or Bottle	43151	3	A/C Jacks
			10	SCHEDULED Corrosion Inspection Pockets (2 Assy)	60 Min.	None	43174	1	
			40	LUBRICATION Fittings 3 Points on ea. Gear (6 Total)	18 Min. (3 each)	Lube Gun	43151	1	Grease
				OTHER SPECIFY					

TABLE XVII

SUMMARY OF MAINTENANCE DEMAND RATES

WUC NUMBER	NOMENCLATURE	QTY. PER A/C	MDR PER 1000 FLIGHT HOURS
13CDA9C	Tire	2	10.00
13EAC	Brake Stack Assembly	2	.78
13EBE	Brake Actuator Assembly	2	.78
13CBL	Strut Hydraulic Actuator	2	.15
13BAA9A	MLG Cylinder	2	.135
13CDA9	Wheel Assembly	2	.125
13BAC1	Downlock Assembly	2	.083
13BAC2	Uplock Assembly	2	.083
13BAQ1	Torque Link-Upper	2	.011
13BAQ2	Torque Link-Lower	2	.011
13BAA9B	MLG Piston	2	.007
13GCB	Anti-Skid Detector	2	.0068
13BAA9C	Axle	2	.005

TABLE XVIII

SUMMARY OPERATIONAL SUPPORT EQUIPMENT
ON-AIRCRAFT MAINTENANCE

OSE NOMENCLATURE	OSE FUNCTION OR DESCRIPTION
Landing Gear Tool Set	Special Tools for Tire, Actuator, Brake and Strut Removal
Air Vehicle Jacks	Three Point Jacking System, 15 Ton Total Load
Dual Purpose GN_2 Servicing Cart	GN_2 Service Cart for Tire Inflation and Strut Servicing (2000 psi)
Hydraulic Servicing Cart	Service Hydraulic System When Replacing Actuators
Hydraulic Fluid Drain Receptacle	Drain Receptacle for Use During Actuator Removal and Replacement Activities (5 Gal.)
Ground Power Electrical Cart 400 Hertz	Provides 400 Cycle Power to Aircraft for Landing Gear Tests
Ground Hydraulic Power Cart	Provides Hydraulic Power for Landing Gear Checkout Following Corrective Maintenance
Anti-Skid Test Set	Provides for Functional Test of Anti-Skid Detector.

TABLE XIX

SUMMARY OPERATIONAL SUPPORT EQUIPMENT
OFF-AIRCRAFT MAINTENANCE

OSE NOMENCLATURE	OSE FUNCTION OR DESCRIPTION
Landing Gear Tool Set (Off Aircraft)	Special Tools and Holding Fixtures Used in the Dissassembly and Assembly of Wheel, Brakes, Actuators, Strut and Sensor.
Dual Purpose GN_2 Servicing Cart	Inflate Tires
Actuator Test Stand-Hydraulic (Intermediate and Depot)	Test Hydraulic Actuators
Clean and Refinish Actuator Stand (Depot)	Clean and Refinish or Resurface Actuators and/or Parts
Gauge Set	Gauge for Inspection of All Landing Gear Precision Parts

The Support Cost is given by the following equation.

Support Cost = Spares Cost + OSE Cost + Personnel Cost

where: Spares Cost = Initial Spares Cost + Recurring Spares Cost

(OSE = Cost of special Operational Support Equipment for all bases.)

Personnel = Cost of Maintenance Airmen and their training.

The Initial Spares cost equation is given below. The quantity of initial spares is adjusted to assure .99 probability of availability.

Initial Spares Cost = Maintenance Demand Rate (MDR)

x Quantity/Aircraft
x Flight Hours/Month/Wing
x Turn-around Time
x Number of Wings
x Unit Cost of Spare

The Recurring Spares cost equation is shown below:

Quantity Recurring Spares = Maintenance Demand Rate (MDR)

x Quantity Per Aircraft
x Total Fleet Flying Hours
x Condemnation Factor

Cost Recurring Spares = Quantity x Unit Cost

The OSE costs have not been calculated since there is no special operational support equipment required specifically for this landing gear system beyond the OSE normally supplied for maintenance of the aircraft.

The Personnel Cost is given by the equation below:

Personnel Cost = Maintenance Demand Rate (MDR)

x Quantity per Aircraft
x Total Fleet Flying Hours
x Cost/Productive Man-Hours
x Maintenance Task Time

where cost per productive manhours includes efficiency, personnel types and training of maintenance airmen.

The Support Cost for the component parts of the baseline landing gear is shown in table XX.

3.2.12 Safety

A safety hazard is caused by the high stress corrosion rate of the baseline landing gear high strength steel components, and this is a contributing factor to the operational costs. Traditionally, only those costs due to scheduled and corrective maintenance have been analyzed, but a safety analysis has also been made on the landing gear to assess the cost due to stress corrosion related accidents predicted to occur over a 10 year operational period.

Data received from Norton Air Force Base on landing gear accidents has been evaluated and the following results and conclusions drawn:

(1) Accidents can be divided into three types:

Minor
Major
Catastrophic

(2) A probability of occurrence can be assigned for each type of accident. This probability can be related to flight hours to derive an accident occurrence rate (AOR).

(3) A cost in percent of total aircraft cost was calculated for each type of accident.

(4) An overall relationship between catastrophic aircraft losses from gear only and total aircraft losses exists. This was modified for those gear related losses which occurred because of stress corrsion.

The following equation was used to calculate accident costs:

$$\text{Cost} = \sum_{x=1}^{3} AOR_x \times TFFH \times POTC_x \times TAC$$

where AOR = Accident Occurance Rate

TFFH = Total Fleet Flying Hours

POTC - Percent of Total Aircraft Cost

TAC = Total Aircraft Cost

$X_{1,\ 2,\ 3}$ = 3 Types of Accidents

TABLE XX

BASELINE SUPPORT COSTS
10 YEAR LIFE SPAN

(All costs are in thousands of 1977 dollars)

WUC NO.	NOMENCLATURE	TOTAL SPARES	PERSONNEL ON A/C	PERSONNEL OFF A/C
	Tire - (13CDA9C)	4,412.4	422.4	192.0
	Brake Stack Assy (13EAC)	235.2	44.9	19.8
	Brake Actuator Assy (13EDE)	156.9	59.9	41.9
	Strut Hydraulic Act (13CBL)	32.3	13.2	8.6
	MLG Cylinder (13BAA9A)	864.6	22.3	6.7
	Wheel Assembly (13CDA9*)	56.0	13.4	2.8
	Up/Down Lock Assy (13BAC1, 2)	45.2	22.3	6.3
	Torque Link Upper (13BAQ1)	8.9	1.0	0.4
	Torque Link Lower (13BAQ2)	8.9	1.0	0.4
	MLG Piston (13BAA9B)	224.6	1.9	0.2
	Anti-Skid Detector (13GCB)	16.3	0.4	-0-
	Axle (13BAA9C)	89.7	1.6	0.2
	Preventative Maintenance		2,793.2	
	Subtotals	6,151.0	3,397.5	279.3
	Personnel Cost		3,676.8	
	Total Support Cost	9,827.8		

The predicted cost of corrosion related accidents over a 10 year period is $18,105,000. This is due to minor accidents costing $510,000, major accidents costing $11,220,000 and catastrophic accidents costing $6,375,000.

3.2.13 Life Cycle Cost

Life cycle cost is the sum of development, production support costs and accident costs. It includes the cost of designing, testing, fabrication and operating the landing gear over the 10 year life span of the air vehicle.

Development or implementation costs include Engineering, Preproduction and Tooling Costs. Section 3.2.8 details these costs which total $1,505,370.

Production costs include both recurring and nonrecurring costs for fabrication of 500 units. The previous section on Production Cost describes the methodology and table XIV presents the results. The total is $41,139,374 and the cumulative shipset cost average at 500 shipsets is $82,279.

The support cost includes the cost of spares, operational support equipment and personnel required to operate the landing gear over a 10 year life span. The previous Maintainability section describes the methodology and table XX lists the support costs. The total is $9,827,800.

The accident costs are given in the previous section and total $18,105,000.

The total Life Cycle Cost is $70,577,000 for the 500 units over a 10 year life span. See table XXI.

TABLE XXI

ATS BASELINE LIFE CYCLE COSTS

(All costs in thousands 1977 dollars)

Development Cost (Nonrecurring)		
Engineering	393	
Two (2) Prototype Sets	378	
Tooling - Preproduction	150	
Test	584	
Subtotal		1,505
Production Cost		
Production Tooling (nonrecurring)	590	
500 Production Units (recurring)	40,549	
Subtotal		41,139
Support Cost		
Spares	6,151	
Personnel	3,677	
OSE	-0-	
Subtotal		9,828
Accident Cost		18,105
GRAND TOTAL		70,577

SECTION IV

DESIGN STUDIES

4.1 PHASE I DESIGN STUDIES

Design studies made for Phase I of this program were to determine the feasibility of using composite material for the B-1 nose landing gear. These studies were made in three section, each having different constraints.

There were:

1. Substitution - Constrained by form, fit and function.
2. Modified - Constrained by fit and function.
3. Redesigned - Constrained by function only.

The studies showed that while some composite parts could be weight and cost effective under all three sections, the more design freedom allowed, the greater the gains from the use of composite material. These studies are presented in Appendix A, the Phase I Report.

4.2 PHASE II CONCEPTUAL DESIGN STUDIES

Design studies made for Phase II of this program were structured to determine the advantages of using advanced concepts and materials for a main landing gear on the ATS, an advanced fighter aircraft. An advanced design configuration of this aircraft, see figure 5, has been used as the baseline, and since it is in this early stage of design, only the "function" general constraint has been used. Conceptual designs using three material systems for the main landing gear have been made. These are:

1. Organic Advanced Composite System,
2. Metal Matrix Composite System, and
3. Advanced Metallic System

The landing gear on this configuration is a conventional tricycle gear, having a nose wheel and two main wheels. The main landing gear struts are mounted in the nacelles, and are stowed in the island between the two engine air inlet ducts. The location of the main gear wheels on the static ground plane, to retain balance for landing performance, is the major constraint to a main gear redesign. The location of the wing structural box, relative to the wheel location described above, constrains both the landing gear configuration and nacelle structure. Configuration of the nacelle may be revised

to accommodate different main landing gear systems. However, the shape of the nacelle near the weapons bay is constrained by the weapon ejection angle. The size of the engine air inlet ducsts must be maintained, but the shape can be varied to allow changes in the center island wheel well area. See figure 7 for nacelle sketch.

4.2.1 Organic Advanced Composites System

Studies in this section of the program were made to investigate landing gear configurations which could exploit the strength and stiffness characteristics of organic advanced composites. Intermediate strength graphite/epoxy composite material was selected on the basis that it provides a good balance between strength and cost. A section on composite material selection is presented in Appendix A, the "Phase I Report."

A number of conceptual designs have been studied. They fall into two groups; one using "leaf spring" concepts in which the composite material is used to absorb the landing impact energy by beam deflection, and the other a "conventional landing gear" concept which uses an air-oil shock strut to absorb the energy. Four concepts were studied and are discussed and evaluated below.

The leaf spring concepts use a series of flat composite plates bonded to resilient material between them. The composite spring plates will deflect under load to absorb the kinetic energy of the landing and the hysteresis property of the resilient material between the leaves will reduce the high energy return (reflex action) of the leaf spring landing gear. Since the energy absorption efficiency of this type of system is much lower than a hydraulic shock strut, the wheel displacement during landing impact will be much greater on the leaf spring concepts.

This concept was studied for the B-1 nose gear in Phase I of this program (see Appendix A) and while it was not considered a viable system for use on the large B-1 bomber, it was felt that it might prove suitable for the landing gear on a smaller airplane such as the ATS fighter.

4.2.1.1 Cantilever "Leaf Spring" Concept. This concept is shown in figure 15 and consists of a five foot cantilever beam with the support trunnions located forward in the nacelle near the duct inlet. A hydraulic cylinder is used to extend and retract the cantilever gear and to lock it into both positions. The wheel is mounted in a fork in the lower end of the cantilever beam.

Vertical and drag landing loads are resisted by the cantilever beam and reacted at the forward trunnion and the locking device. Side loads on the

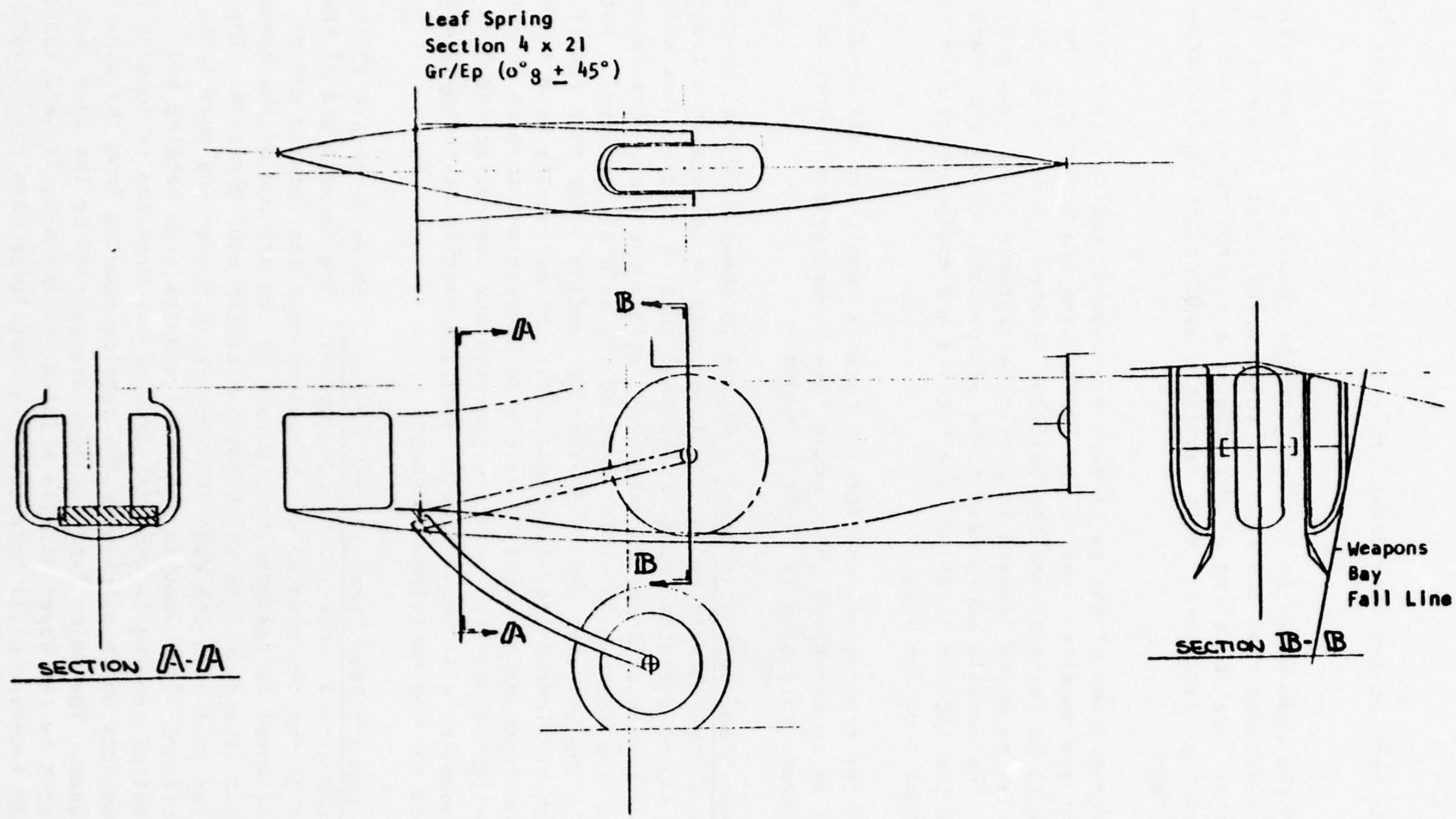


Figure 15. Cantilever "Leaf Spring" Concept

wheel create side bending and very undesirable torsion on the cantilever leaf spring beam.

The size of the beam shown in figure 15 is the result of a rough sizing calculation which assumed that the beam was solid Gr/Ep, that the material was homogenous and that local buckling of the fibers is controlled by a retaining overwrap or mechanical fasteners. More realistic assumptions would increase the size of the beam.

The large forward end of the cantilever beam would require major revisions to the duct and nacelle lines to provide stowage space for it. The ducts would have to be reshaped and the splitter widened. This would require that the duct inlet be moved forward to provide acceptable inlet ramp angles and duct lines. The nacelle would have to be widened and, since the weapon fall line limits the inboard location, the nacelle and engine would have to be relocated outboard on the wing.

Location of the trunnion in the forward nacelle results in all landing loads being applied to structure which would have to be resized since, in the baseline concept, this area is lightly loaded.

4.2.1.2 Dual Beam "Leaf Spring" Concept. Figure 16 shows this dual beam configuration in which the forward end of the lower beam is mounted in a trunnion and the forward end of the upper beam is fastened to a retracting link which is moved by the actuator cylinder to extend or retract the gear. The lower end of each beam is a fork which is fastened to the axle of the wheel. Both beams are bent in the unloaded condition and the landing loads then result in axial loads which straighten the lower beam while increasing the bend in the upper beam. Side loads on the wheel create side bending and torsion in both beams. This configuration, with both the trunnion and the retracting link forward in the nacelle, will require major duct and nacelle revisions similar to those required for the cantilever concept.

4.2.1.3 Center Support Beam "Leaf Spring" Concept. Shown in figure 17 is a "leaf spring" beam with a center down lock support. The forward end of the beam is fastened to the trunnion which is located near the forward end of the nacelle. The wheel is fastened to the fork at the aft end of the beam. The center support is a down lock which has a "ladder" configuration. The actuation cylinder will hold the down lock "on center" when the gear is in the extended position. Side load on the wheel creates side bending and vertical differential bending in the fork arms of the beam and is reacted by the "ladder" down lock which eliminates the torsion loading from the upper section of the beam. The major landing loads are carried by the down lock center beam support to the upper nacelle adjacent to the wing forward spar, however, the beam trunnion still introduces landing loads into the forward nacelle area.

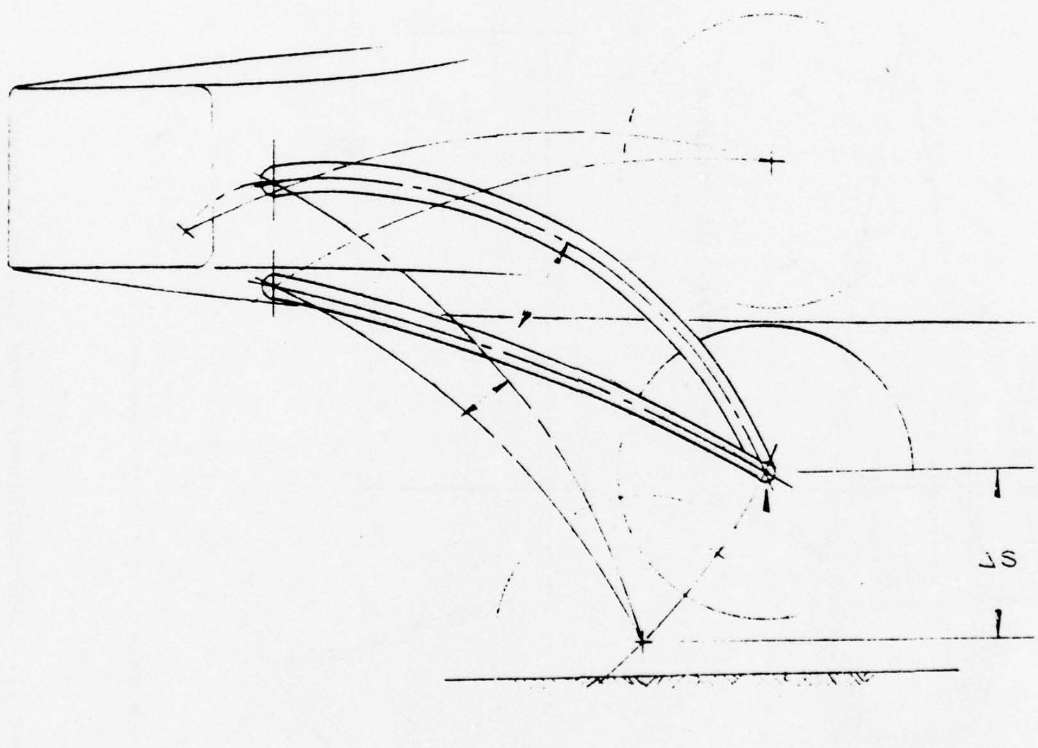


Figure 16. Dual Beam "Leaf Spring" Concept

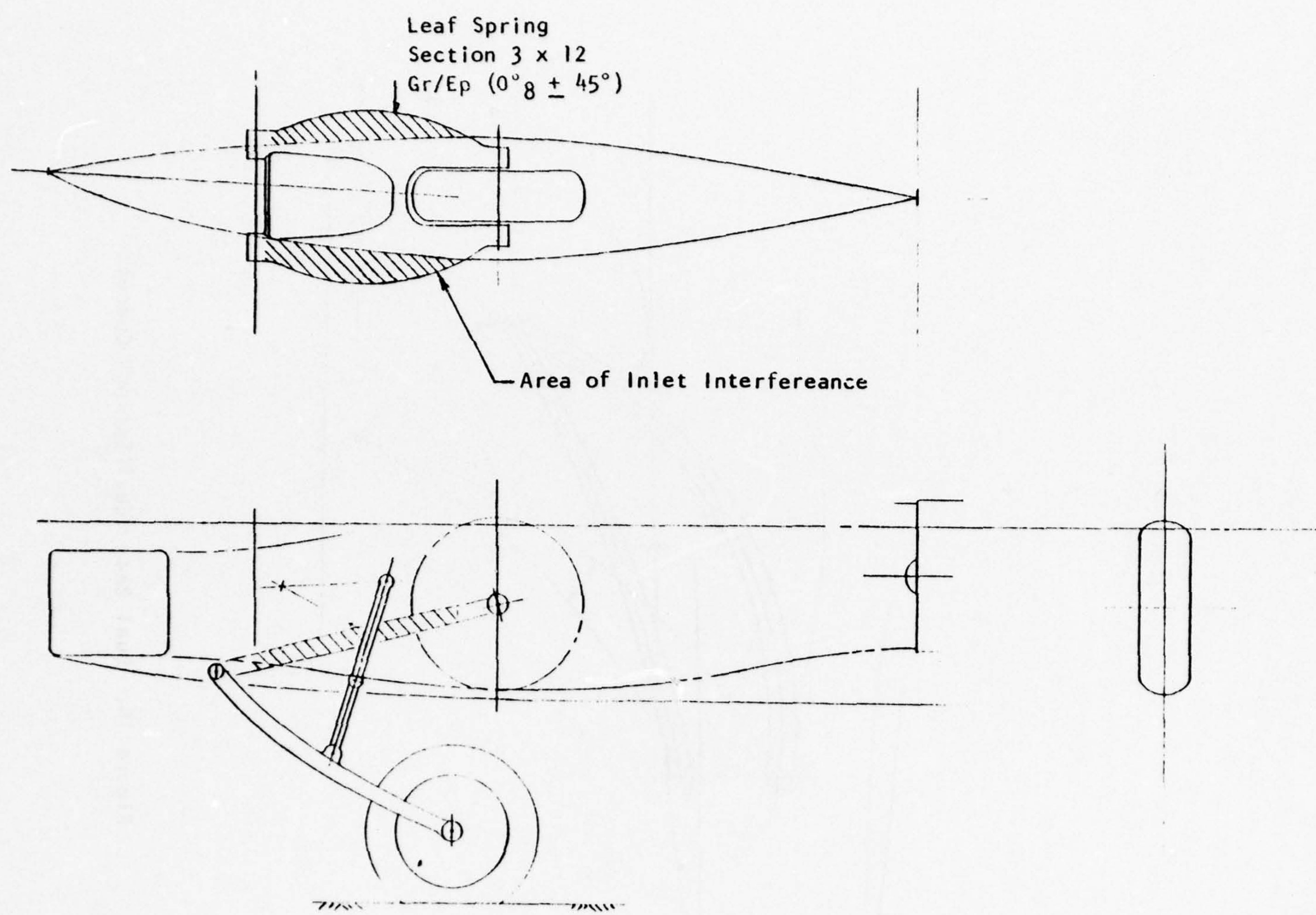


Figure 17. Semi-Cantilever "Leaf Spring" Concept

The beam size shown in figure 17 is the result of a rough sizing calculation similar to that made for the cantilever beam. It indicates that this version also would require major changes to the duct and nacelle lines and structural sizing, similar to that for the cantilever beam concept.

4.2.1.4 Organic Composite Conventional Landing Gear Concept. This design uses a semicantilevered shock strut having a configuration similar to the baseline landing gear. The strut uses an air-oil shock absorption system to absorb the energy of landing, and to support the airplane weight. This strut has trunnions low on the body of the strut and a latch on top which allows the strut to react all loads without the need for drag braces.

Vertical loads are reacted by trunnions which are fastened to the side walls of the duct. Drag loads and moments are reacted by the trunnions and the upper latch. Side loads and moments are reacted by the trunnions. Torsion loads between the fork (piston) and strut body are reacted by two torque links. The lower torque link is mounted between lugs on the axle socket of the fork and the upper torque link is fastened to the strut body by the trunnion pin.

The composite strut is housed within the island between the air intake ducts of the nacelle. This is similar to the baseline installation except that, since the composite strut and fork must be larger, the island must be widened to accommodate the gear. The outer diameter of the composite strut is 9.80 inches compared to the baseline struts outer diameter of 5.85 inches. The island has been widened to 21 inches maximum from the 18 inch maximum width of the baseline.

In order to avoid increasing the overall width of the nacelle, the shape of the duct has been revised to retain the required duct area while narrowing the duct. The lower contour of the nacelle has been revised from a rounded to a squared-off shape. This allows the height of the duct section to be increased by extending it down into the lower corners of the nacelle. The location of the inboard lower corner of the nacelle was constrained by the weapon system ejection line, see figure 18. These changes will increase both the frontal area and the weight of the air vehicle.

4.2.1.5 Organic Advanced Composite Concept Evaluation. The three leaf spring concepts all have the same major installation problem in that the duct and nacelle lines and the forward nacelle structure sizing would require major revisions to accommodate any of these concepts. This is caused by the requirement that the extended wheel location be fixed, relative to the aircraft C.G., and that a long beam is required to provide the large wheel displacement necessary to absorb the landing impact energy with this system.

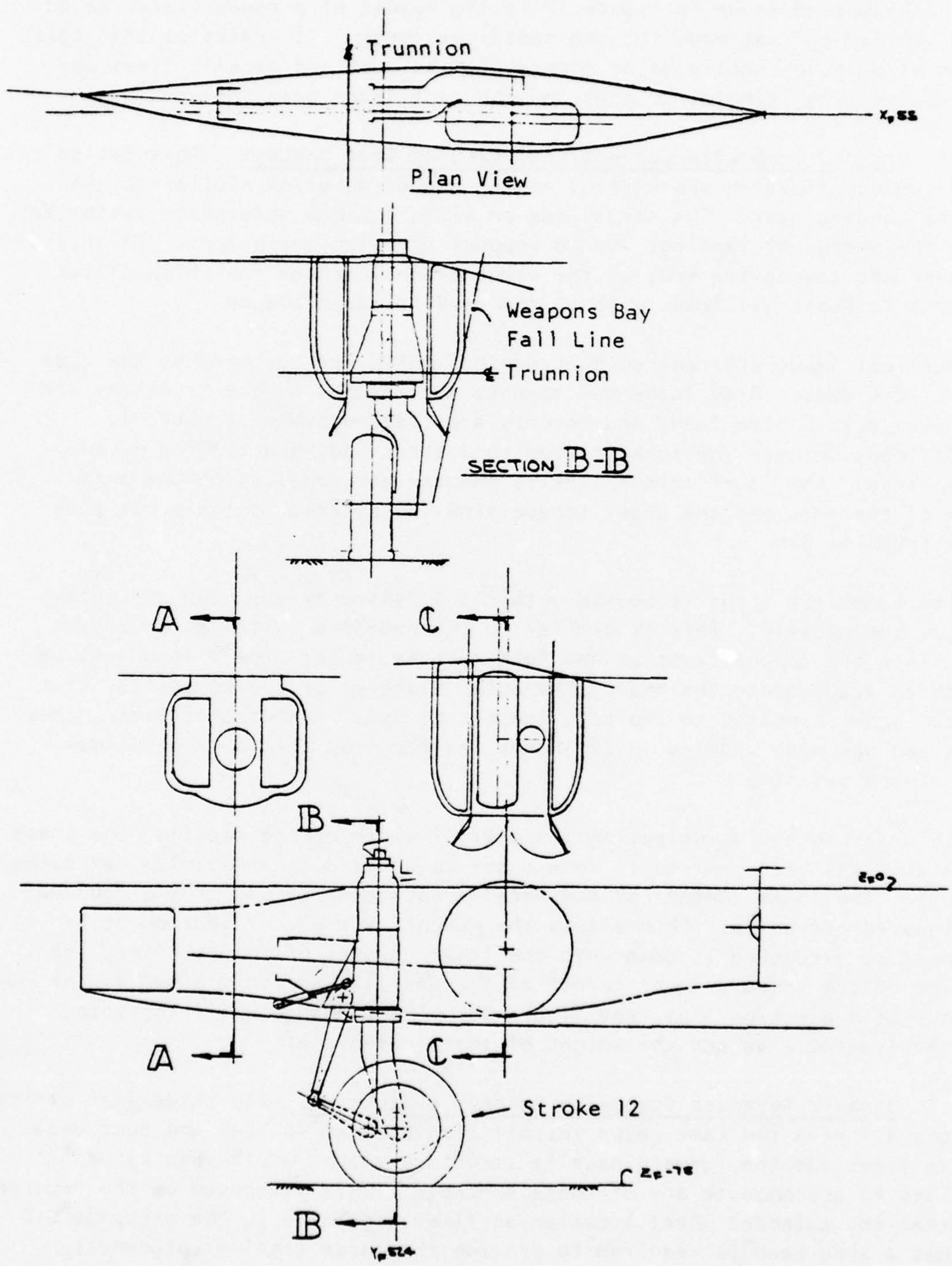


Figure 18. Conventional Landing Gear Organic Advanced Composite

With a given load and beam material, the beam deflection and the rate of displacement is a function of the size of the beam. The length has been kept large so that the gross section width can be minimized and allowable stress levels maintained. The beam sizes required for any of the concepts were very large and could not be installed without the nacelle revisions previously mentioned. These large beams would also be very heavy. An extensive development program would be required to provide data on the energy absorption qualities of a layered beam using composite material interleaved with resilient material. The characteristics of the resilient material and its ability to absorb energy due to hysteresis effect must be defined. Effect on the performance of the beam due to methods of fastening the leaves together, whether by adhesive, fasteners or over wrap, must be determined. After development of the materials, methods and design, manufacturing procedures for fabrication of the layered leaf spring beam must be developed.

From the above discussion, it has been concluded that, at this time, the leaf spring configuration would not be a viable landing gear concept.

The conventional landing gear concept uses the more efficient hydraulic shock strut to absorb the landing impact loads. The changes to the ducts and nacelle, to provide the extra three inches width in the duct splitter necessary to stow the strut, would be moderate, compared to that required for the leaf spring concept.

Table XXII summarizes the comparison between the leaf spring concepts and the conventional landing gear concepts. The conventional landing gear concept has been selected as the best Organic Advanced Composite concept, and will be used in the evaluation against the best Metallic Matrix Composite concept and the best Advanced Metallic concept.

4.2.2 Metal Matrix Composite System

Metal matrix composites offer numerous advantageous material characteristics for use in highly loaded components of a landing gear. They include high intrinsic strength, and high specific strength and moduli. In addition, it is a tailorable composite material which may be fabricated into parts having specific strength and stiffness to resist bi-axial or tri-axial loads and thus use minimum material thickness to save weight. The material is highly stable, has desirable high temperature properties, and in some applications, has the potential for reduced fabrication costs.

The metal matrix composite system most closely approaching a state-of-the-art technology is boron/aluminum (B/Al). This composite consists of boron filaments diffusion bonded into an aluminum matrix. To date, more material and design data has been generated in support of this material

TABLE XXII

EVALUATION - ORGANIC ADVANCED COMPOSITES CONCEPTS

CONCEPT	MAJOR PARTS	REQUIRED DEVELOPMENT PROGRAM	FABRICATION	WEIGHT	NACELLE STRUCTURE REVISIONS	COST ESTIMATE	SHOCK ABSORPTION SYSTEM
Cantilever	Beam Upper Fitting Lower Fitting Lock Device	Major	Very Difficult	Heavy	Very Extensive	Very High	Bending Beam
Dual Beam	Beams (2) Upper Fittings (2) Lower Fittings (2) Upper Arm Lock Device	Major	Very Difficult	Heavy	Very Extensive	Very High	Bending Beam
Center Support Beam	Beam Upper Fitting Lower Fitting Center Fitting Upper Link Lower Link Lock Device	Major	Very Difficult	Heavy	Very Extensive	Very High	Bending Beam
Conventional Landing Gear	Piston/Fork Cylinder Torque Links (2) Lock Device	Minor	Difficult	Lightest	Moderate	Moderate	Hydraulic Shock Strut

system than any other metal matrix composite. Application programs for design analysis, fabrication process development, and hardware development of airframe and engine application have been conducted.

Major component fabrication programs such as the B-1 boron/aluminum wing root-rib web have demonstrated that metal matrix composites may be substituted for high strength alloys (i.e., titanium) with appreciable weight and cost savings (33 percent and 45 percent respectively).

The boron/aluminum material system has been selected as the metal matrix composite to be used in this study. There are three primary methods of fabrication used in boron/aluminum production. The first is "green tape" which is boron fibers attached to a green disposable carrier paper by acrylic binders. This material, when laminated with aluminum foil plies, may be consolidated by diffusion bonding at high temperature and pressure, while maintaining a vacuum environment on the part to extract the acrylic binder as it gassifies. The improper "out gassing" of this material entraps the acrylic binder between fiber and matrix and is probably the single largest cause of improper material consolidation and lower material properties.

The second method of B/Al fabrication is through the stacking and diffusion bonding of "plasma sprayed" sheets or tape. Parts made using this method would be more costly due to the difficulty and expense of the plasma spray process.

The third method, and probably the method of least technical risk, though not the least costly, is the consolidation by diffusion bonding of stacked "monolayers." Monolayers are single laminate plies, produced as a tape which are generally diffusion bonded to 75 to 80 percent consolidation. It is this intermediate diffusion bonding step which inhibits the cost savings potential of this material, but which greatly reduces the risk of processing to the finished product.

Boron/aluminum composite material, correctly processed by any of the three methods, will result in material having very similar properties. However, the plasma sprayed tapes have the least attractive material properties of the three.

Some typical properties of boron/aluminum are:

Density = .093 pounds per cubic inch
Ultimate Tensile Strength - 230,000 pounds per square inch
Modulus of Elasticity - 34×10^6 pounds per square inch
Specific Strength = 2.5×10^6 inches
Specific Modulus = 3.7×10^6 inches

A more complete summary of properties for boron/aluminum may be found in AFML-TR-72-232.

A review of the three processes indicates that the monolayer process, on the basis of lower technical risk, should be selected as the fabrication method for this study.

Diffusion bonding to effect material consolidation is the major feature of all three processes. This in turn makes tooling feasibility the design driver in applying metal-matrix composites to the landing gear or other complex airframe systems.

Conceptual designs using a number of different configurations have been studied to determine which may be best integrated into the airframe and most advantageously use boron/aluminum components. Five concepts have been studied (A through E), and will be discussed and evaluated below.

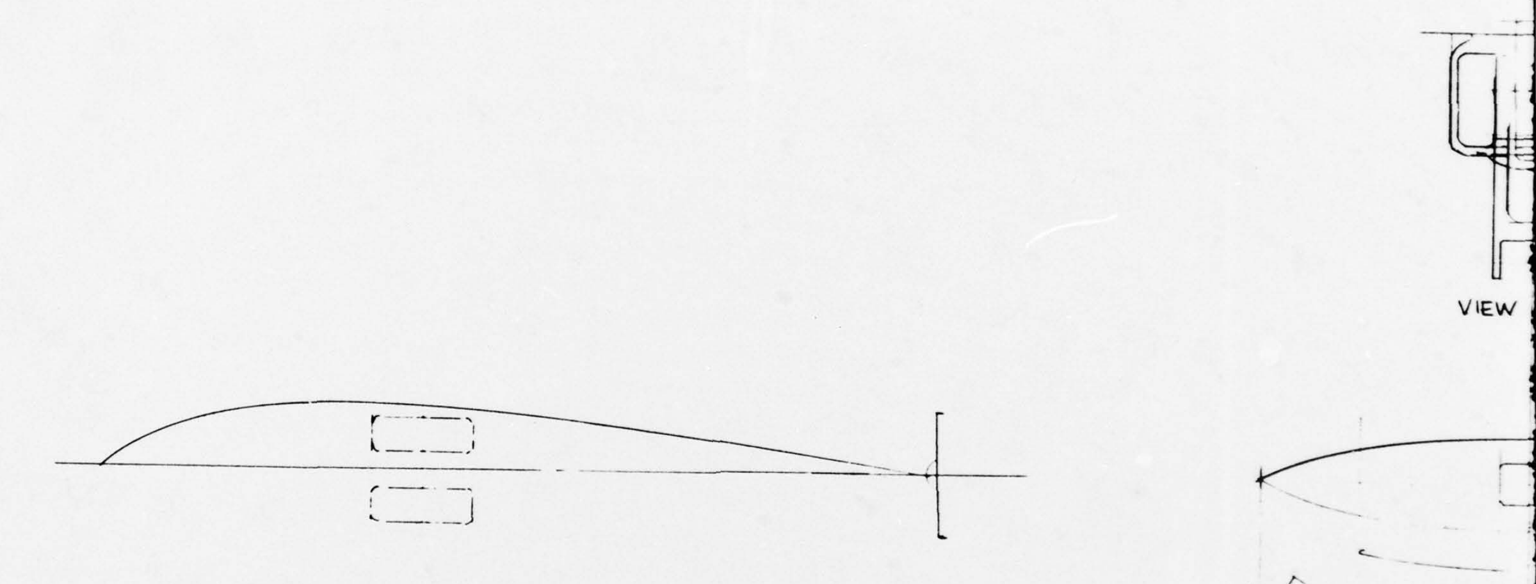
4.2.2.1 Boron/Aluminum Concepts A and B. Two versions of a folding drag link configuration as shown in figure 19. Concept A uses dual wheels and Concept B a single wheel. Both concepts use an aft canted air-oil shock strut with a forward folding drag brace. Retraction from the extended position for both concepts requires folding of the drag links and rotation of the shock strut and wheel up and forward.

In Concept A the dual wheels are mounted on an axle that is supported by the lower drag link which is fastened to the piston of the shock strut. The single wheel in Concept B is supported by two forks, one on the lower drag link and one on the strut piston.

The wheel well width requirements for the dual wheels is 32 inches, a 14 inch increase over the baseline. The duct splitter and nacelle could not be widened that much without lengthening the nacelle and relocating the nacelle and engines outboard on the wing. This would result in too great a penalty to the aircraft for Concept A to be considered a viable configuration.

Using a single wheel, Concept B requires only a five-inch increase in wheel width over the baseline. However, the location of the stowed wheel forward in the duct results in an unacceptable distortion of the baseline duct lines. The nacelle would have to be lengthened to make the duct inlet lines acceptable. The forward location of the drag brace trunnions result in landing loads being introducted into the forward nacelle area structure which would require resizing to react these loads.

4.2.2.2 Boron/Aluminum Concept C. Concept C is shown in figure 20, and uses a vertical air-oil shock absorber mounted on two retracting links with a



DUAL WHEELS

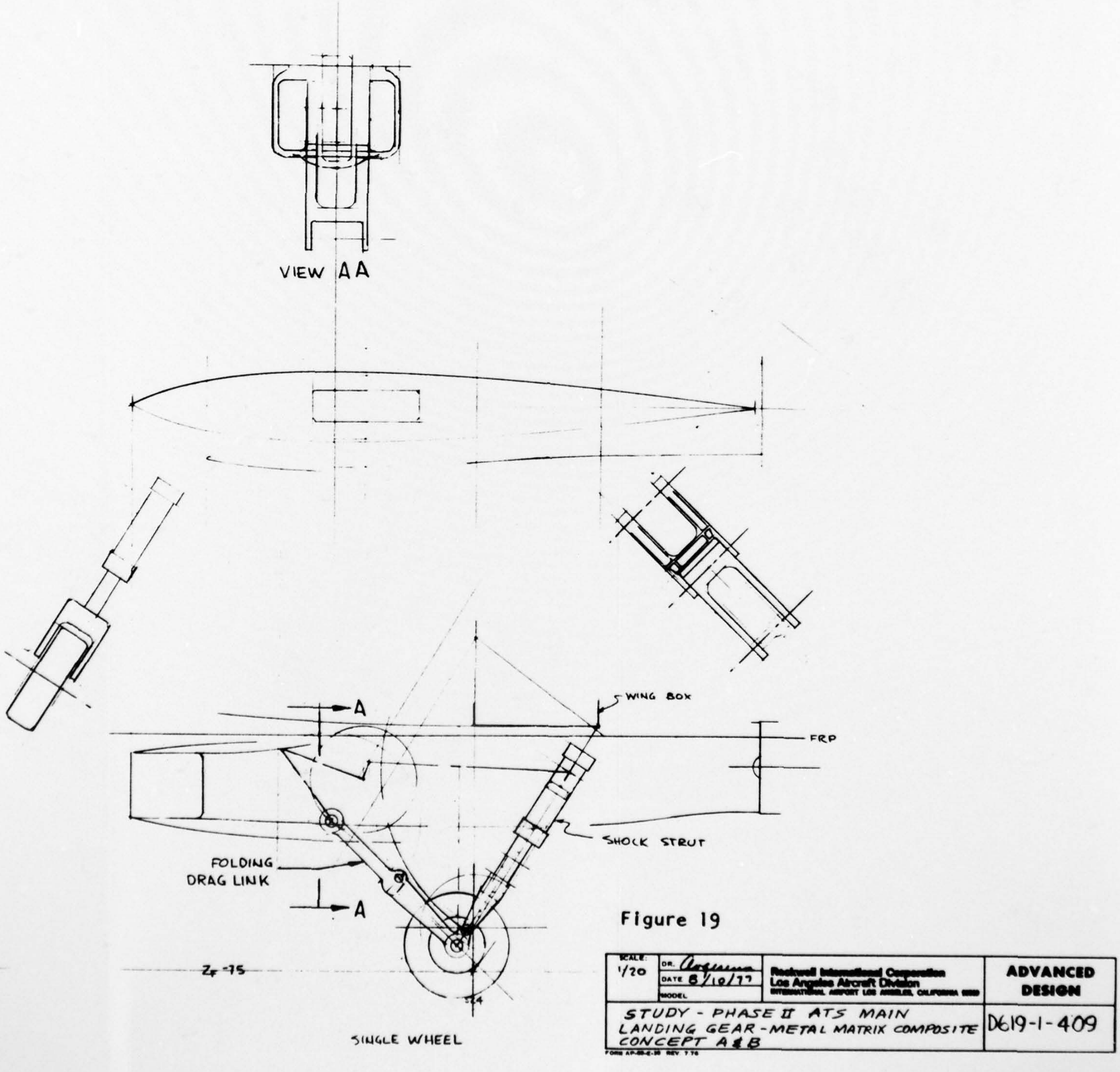
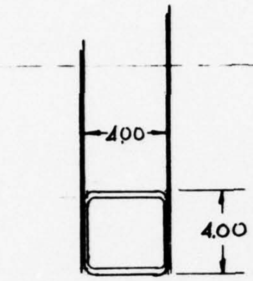
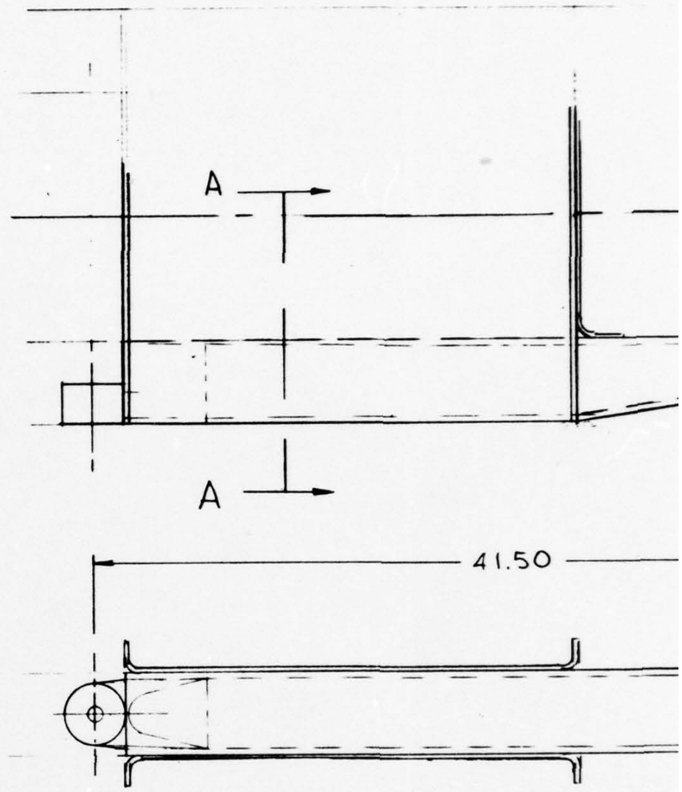

VIEW AA
A
A
WING BOX
FRP
SHOCK STRUT
FOLDING DRAG LINK
Z_F -75
SINGLE WHEEL
SCALE: 1/20
DR.
DATE 8/10/77
MODEL
Rockwell International Corporation
Los Angeles Aircraft Division
ADVANCED DESIGN
STUDY - PHASE II ATS MAIN LANDING GEAR - METAL MATRIX COMPOSITE CONCEPT A & B
D619-1-409

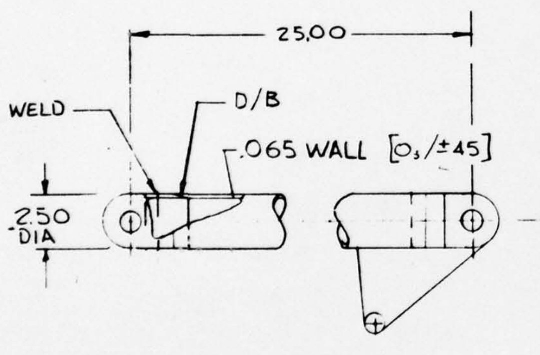
Figure 19



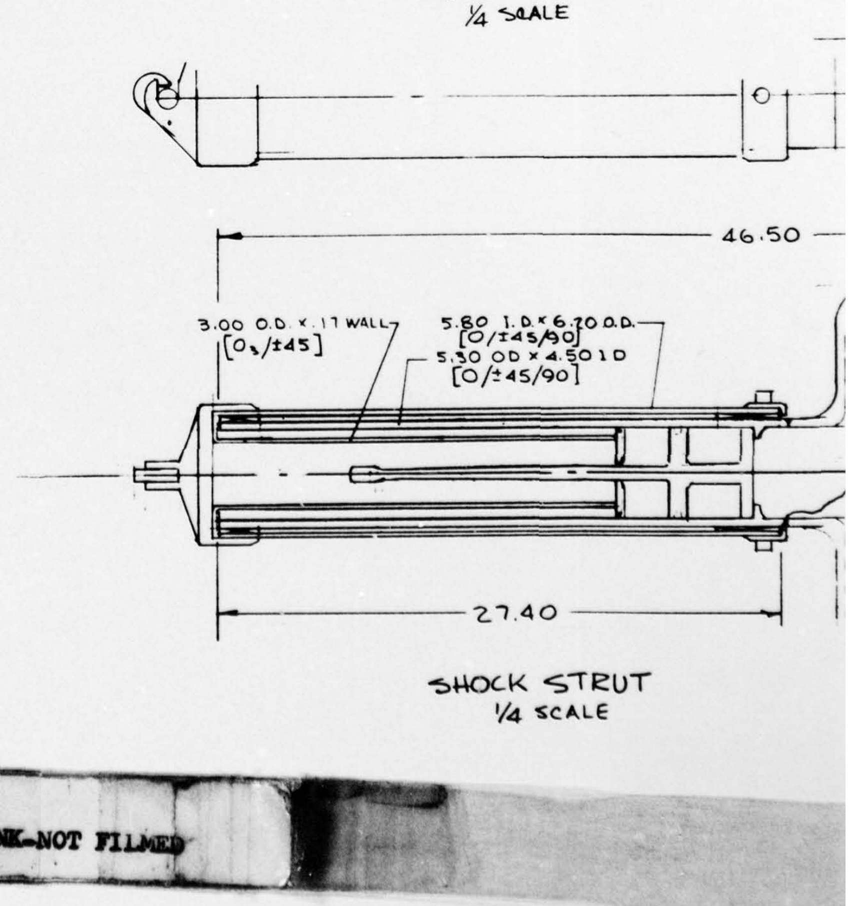
SEC A·A



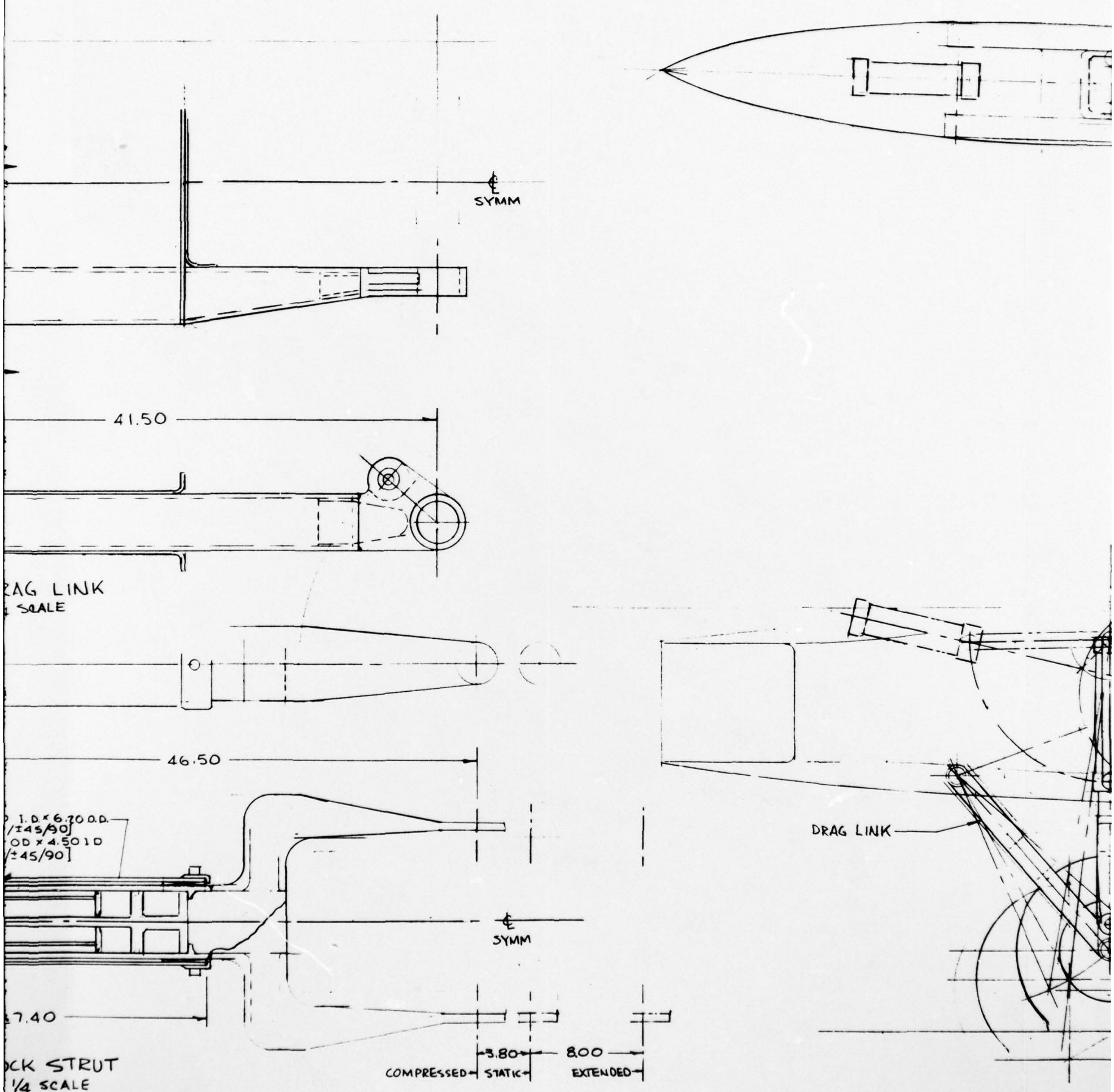
DRAG LINK
1/4 SCALE



RETRACTING LINKS
1/4 SCALE

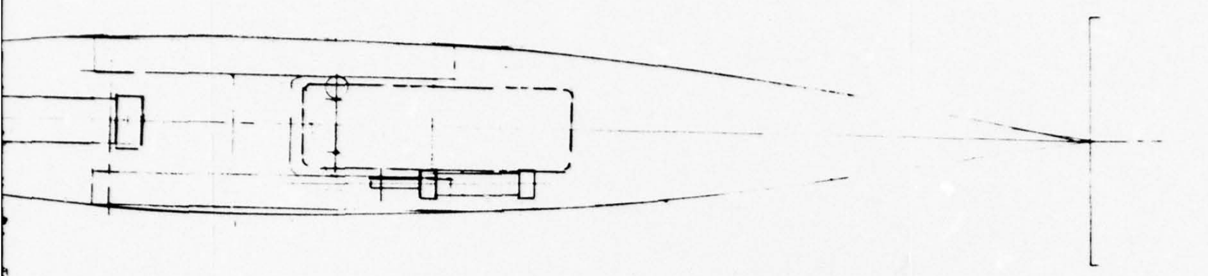


SHOCK STRUT
1/4 SCALE



SYMM
41.50
RAG LINK
SCALE
46.50
I.D × 6.70 O.D.
[±45/90]
OD × 4.50 I D
[±45/90]
SYMM
7.40
CK STRUT
1/4 SCALE
3.80
8.00
COMPRESSED
STATIC
EXTENDED
DRAG LINK

2



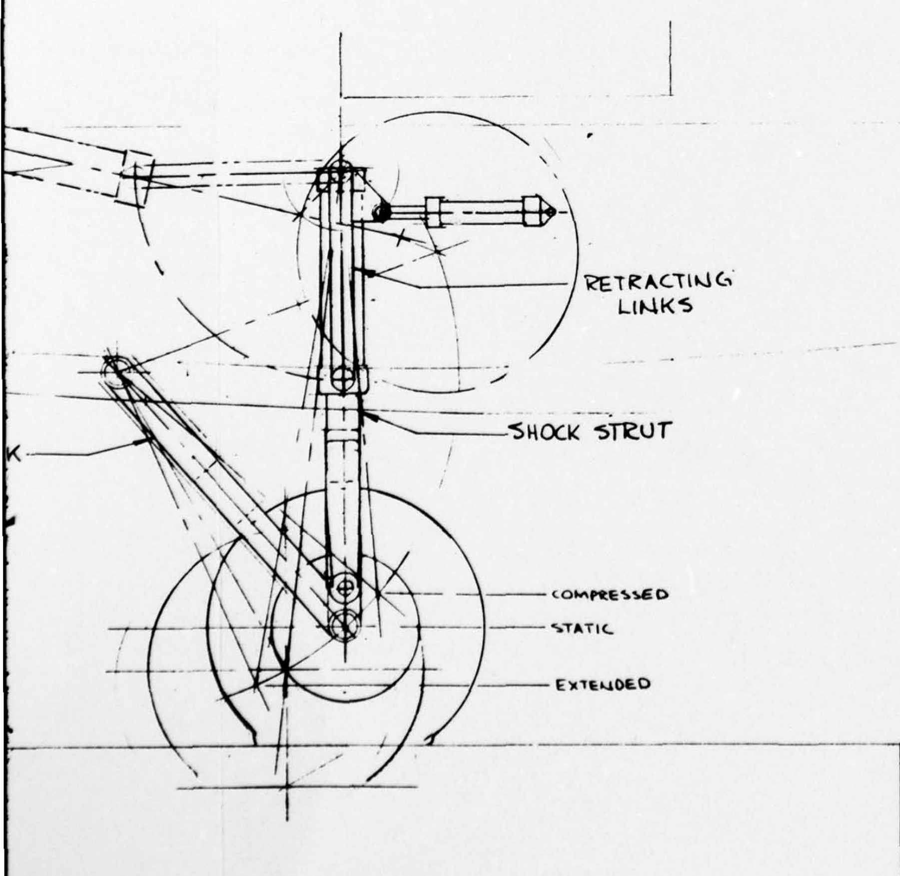


Figure 20

SCALE: 1/10 NOTED	DR. / DATE 8/10/77 / MODEL	Rockwell International Corporation, Los Angeles Aircraft Division	ADVANCED DESIGN
STUDY-PHASE II ATS MAIN LANDING GEAR METAL MATRIX COMPOSITE-CONCEPT C			D619-1-410

forward nonfolding drag link. This gear is retracted by rotating links up and forward which pulls the strut up and rotates the drag link up into the stowed position.

Vertical landing loads would be reacted by the strut into the retracting arms and the upper trunnions. Drag loads would be reacted by the drag strut and the forward trunnions. The side loads on the wheel will induce side bending and torsion into the drag brace and bending in the shock strut. The retracting links will be subjected to axial loads only.

Both the drag link and the piston of the shock strut have double forks supporting the wheel. The shock strut is supported low on the cylinder by the retracting links which are tubular struts fastened to the main trunnions. The cylinder and piston of the strut would be B/Al, but the fork section would be titanium. The drag strut and the retracting links would be B/Al, diffusion bonded to titanium end fittings.

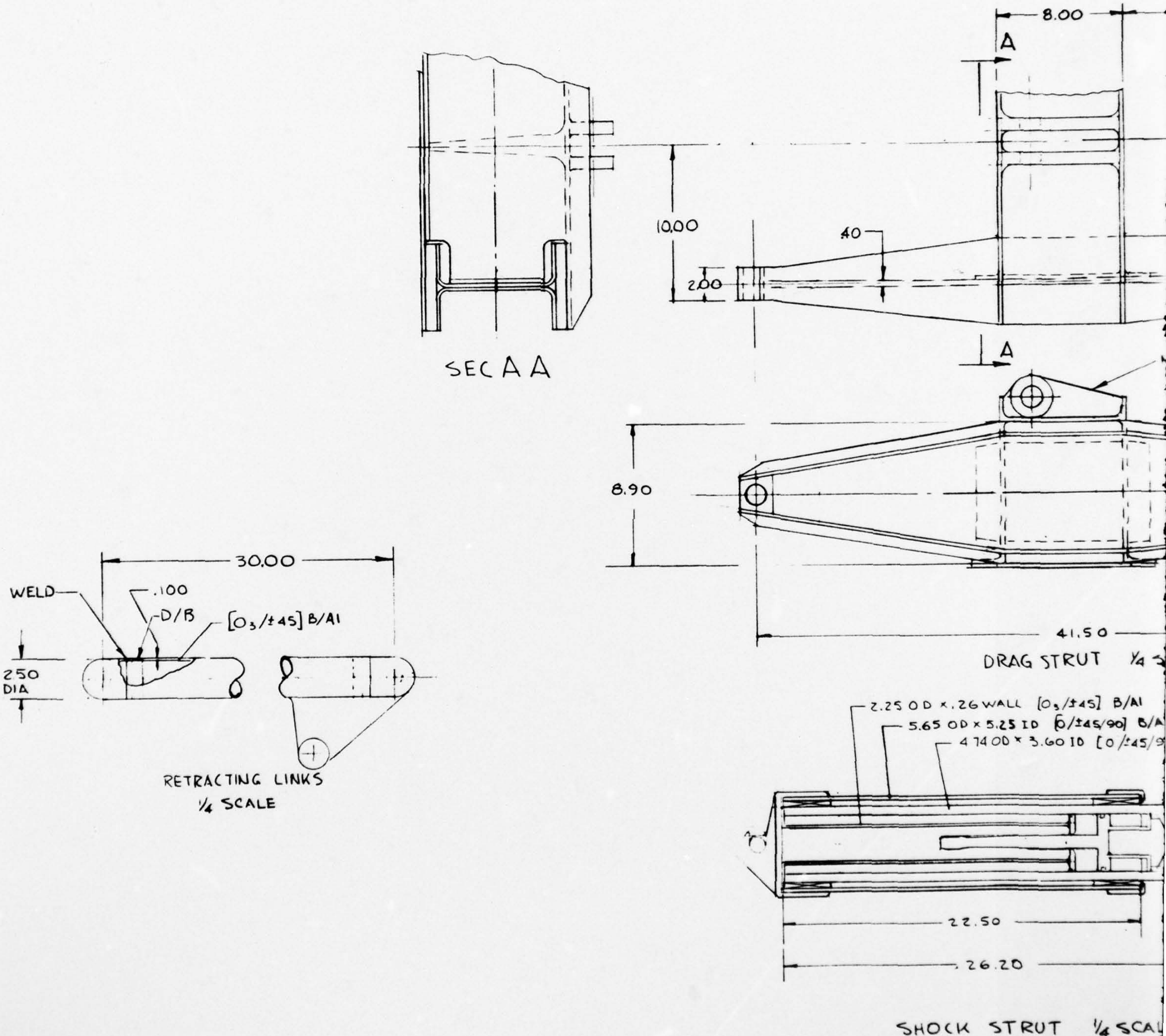
The main trunnions are located high in the wheel well directly under the front spar of the structural wing box. This results in a very short and direct load path for the major landing loads. However, the location of the drag brace and forward trunnion in the nacelle would require resizing of the structure in the forward nacelle to react the drag and side landing loads. The width of the wheel well must be increased six inches over the baseline to provide for this concept. Revision of both duct and nacelle lines would be required to meet the duct sizing requirements.

4.2.2.3 Boron/Aluminum Concept D. A "trailing arm" configuration, Concept D, is shown in figure 21. The wheel is mounted in a double fork on the trailing arm, which is supported by the forward trunnions and the shock strut near the center of the beam. This concept has the air-oil shock strut supported by two retracting links, and operation is similar to Concept C.

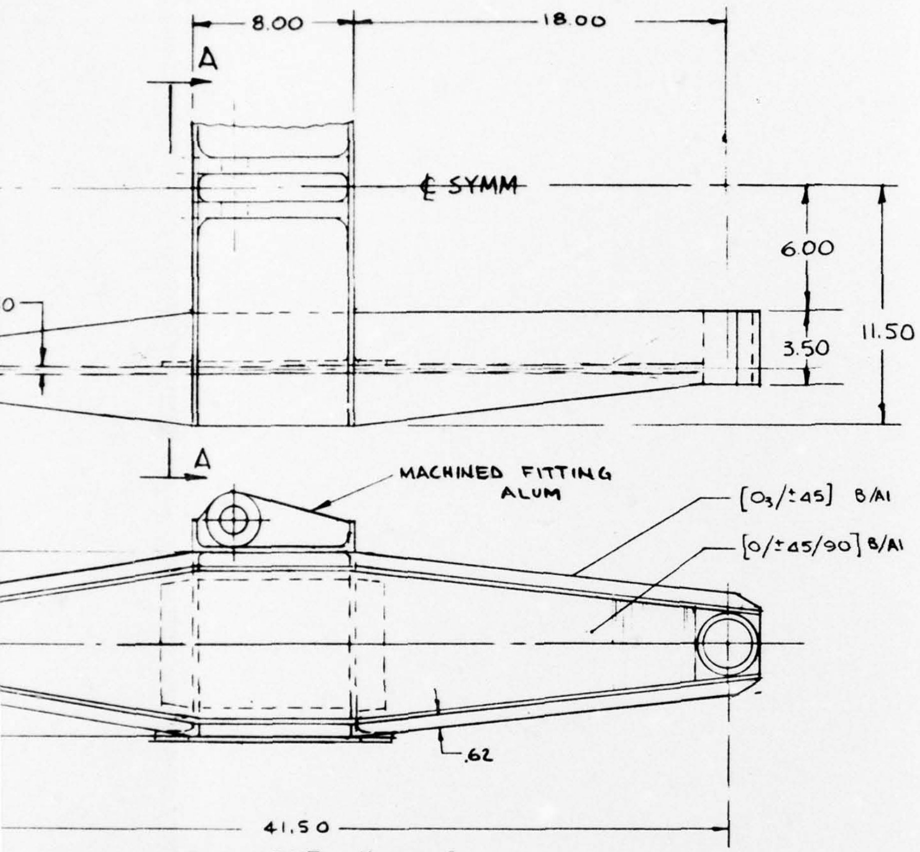
Vertical and drag loads induce bending into the trailing beam and are reacted at the forward trunnions and the shock strut mount. Side load on the wheel results in side bending and torsion on the trailing beam and bending in the shock strut. Axial loads in the retracting links result from the landing loads and bending in the strut.

Parts proposed to be made from boron/aluminum are the cylinder and piston of the shock strut, the beams of the drag brace, and the retracting links. The caps and end fittings will be titanium, and the shock strut mount fitting on the beam would be machined aluminum.

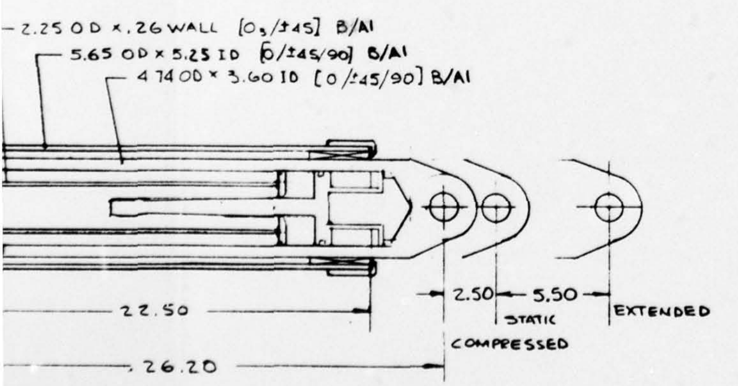
This configuration reacts major landing loads at the front trunnions from the trailing beam, as well as at the aft trunnions from the shock strut.



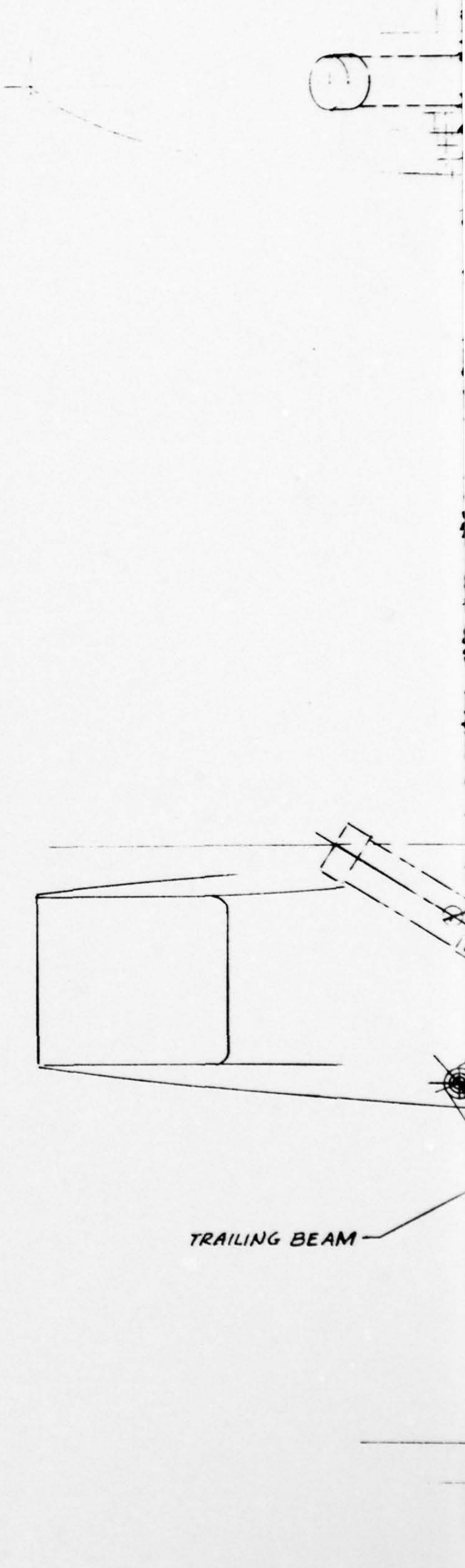
PRECEDING PAGE BLANK-NOT FILMED



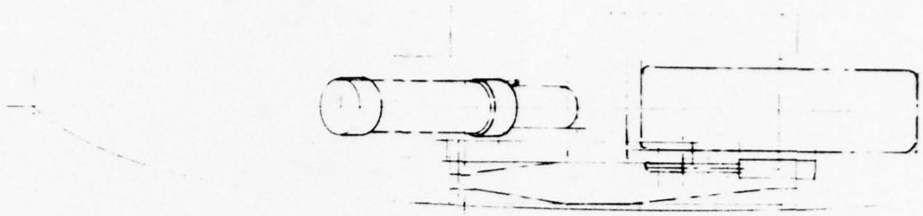
DRAG STRUT 1/4 SCALE

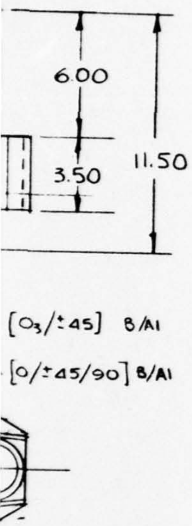


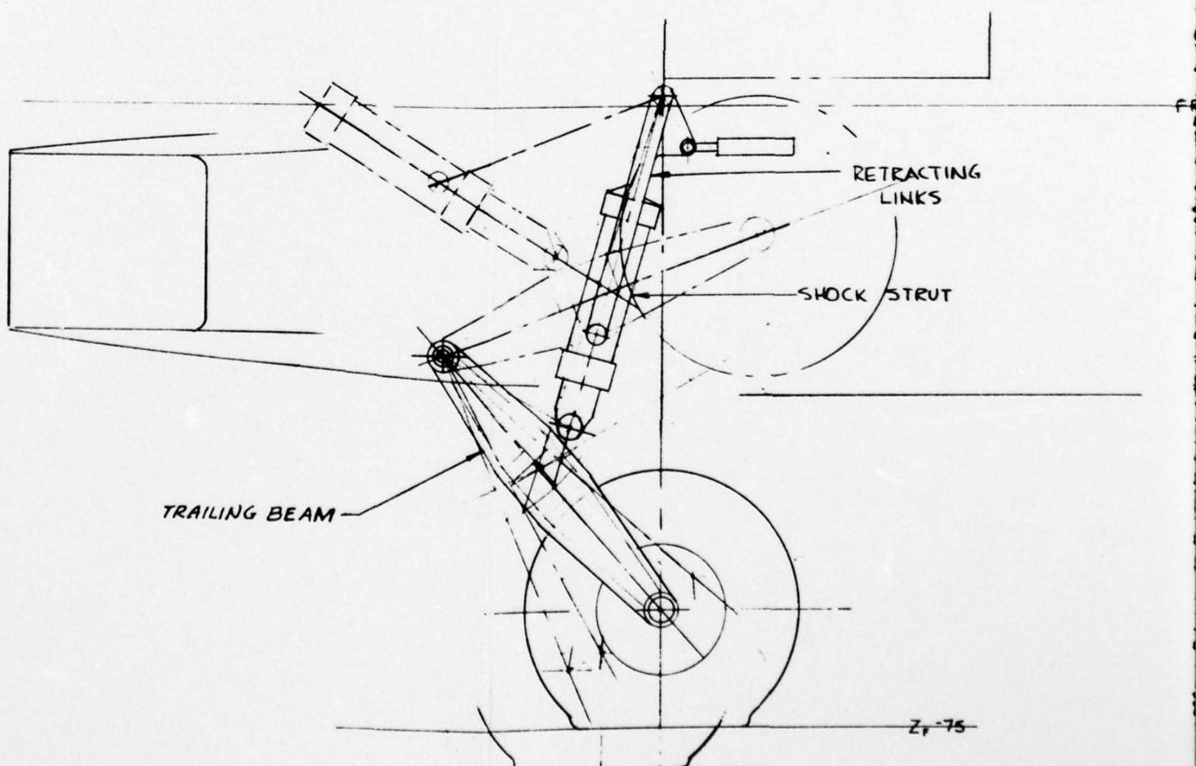
SHOCK STRUT 1/4 SCALE



8




6.00
3.50
11.50
[O3/±45] B/Al
[0/±45/90] B/Al


RETRACTING LINKS
SHOCK STRUT
TRAILING BEAM
Z, -75

4

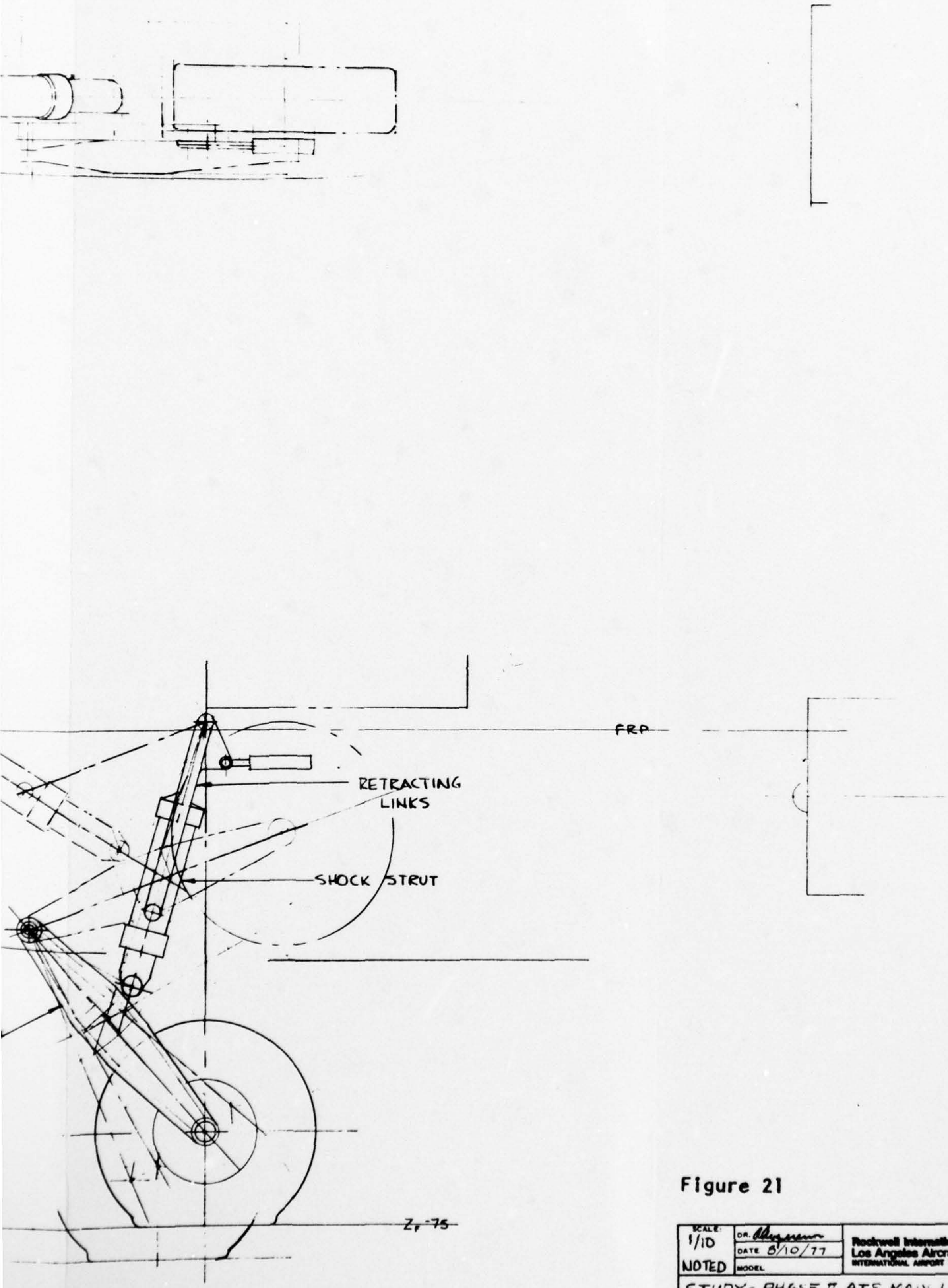


Figure 21

SCALE 1/10 NOTED	DR. [signature] DATE 8/10/77 MODEL	Rockwell International Corporation Los Angeles Aircraft Division INTERNATIONAL AIRPORT LOS ANGELES, CALIFORNIA	ADVANCED DESIGN
STUDY - PHASE II ATS MAIN LANDING GEAR METAL MATRIX COMPOSITE - CONCEPT D			D619-1-411

FORM AP-00-E-30 REV 7.76

4

4

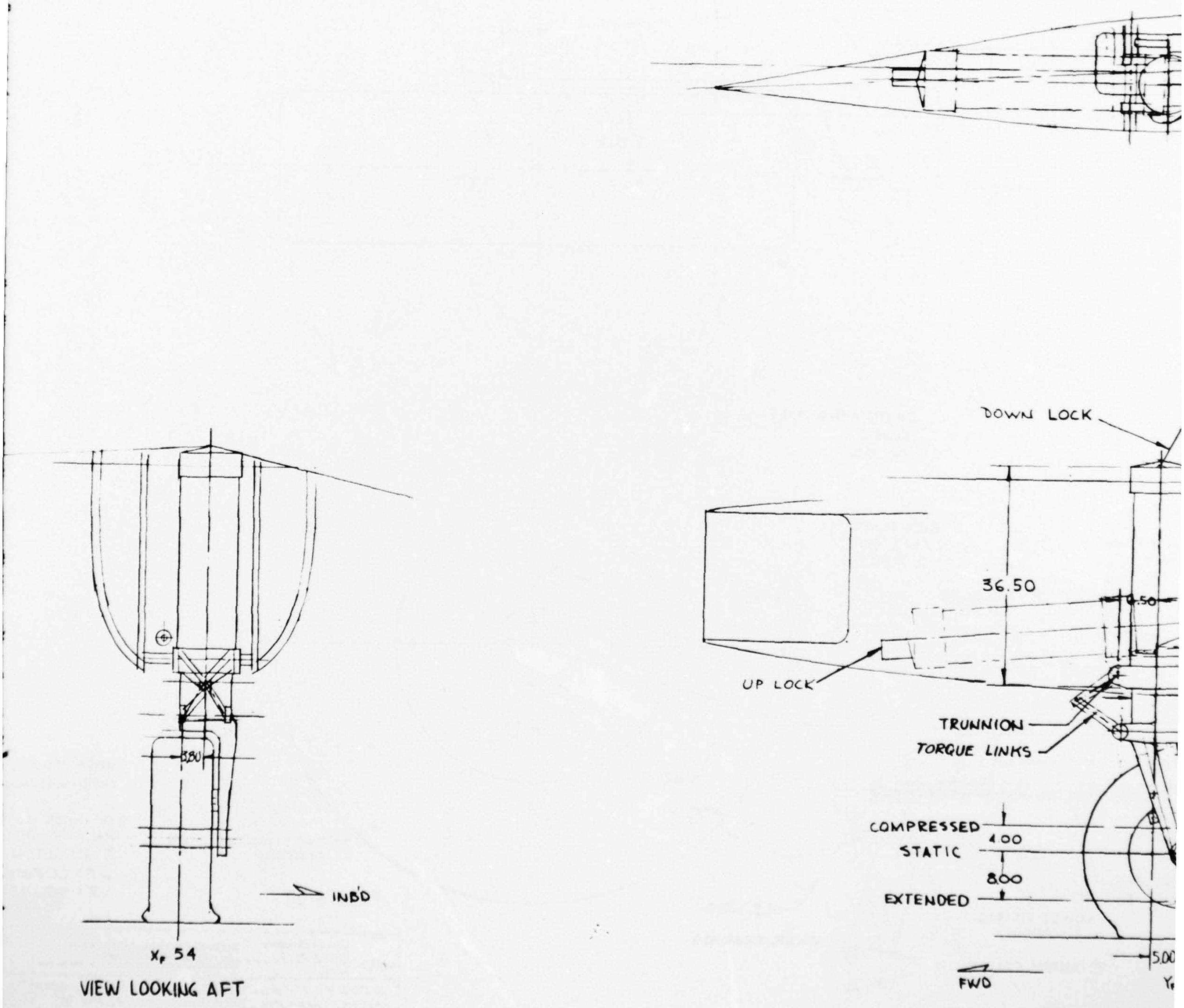
Thus, while the aft trunnion is very well placed to react loads directly into the forward spar of the wing structural box, the forward trunnion is located forward in the nacelle where the structure must be resized to accommodate the major landing loads introduced by the forward end of the trailing beam. Increased room in the wheel well must be provided for this concept. The duct splitter must be widened six inches over the baseline. Line changes to maintain duct area while reducing the width of the duct, and nacelle changes to accommodate the duct, would be required.

4.2.2.4 Boron Aluminum Concept E. Figure 22 shows Concept E, a conventional landing gear configuration which has a cantilevered air-oil shock strut which is the main structural member as well as the energy absorbing device. This configuration is similar to the baseline configuration which was described in Section III. The strut mounts on trunnions, low on the strut, and locks into the extended and retracted position by use of a latch on top of the strut. A single fork supports the axle and wheel which simplifies anti-skid sensor installation and removal of wheels and tires. Vertical loads are transferred from the strut to the trunnions. The drag loads are resisted by the strut trunnions and the upper latch. Side loads are reacted by the trunnions.

The shock strut, shown in figure 23, is an air-oil type and parts proposed as B/Al include the strut cylinder, orifice and support tube, the piston and the metering pin base plate. The torque links are also proposed as B/Al. Titanium end fittings would be diffusion bonded to the ends of both the B/Al strut cylinder and the piston. The upper strut cap and the lower trunnion lug fittings would be machined titanium. The fork is proposed as a powdered metalurgy hot isostatic pressed titanium casting which would be electron beam welded to the titanium end fitting on the B/Al piston.

The trunnions are located below and just forward of the structural wing box, similar to the baseline configuration, with the advantage of the short load path. The stowage area in the duct splitter would have to be slightly widened to 19 inches from the 18 inch baseline dimension.

4.2.2.5 Metal Matrix Composite Concept Evaluation. Concept A is not considered a viable configuration since the width requirements would force unacceptable changes to the air vehicle. Concepts A, B, C, and D kinematics are good in that the wheel motion after landing impact is advantageous for absorbing spinup loads and reducing spring back loads. These concepts have a larger number of major parts than Concept E, the conventional type landing gear. Concept D is estimated to be the heaviest concept due to the long trailing beam loaded in bending. Concept E, with fewer parts, is estimated lightest.



VIEW LOOKING AFT

R.H. GEAR

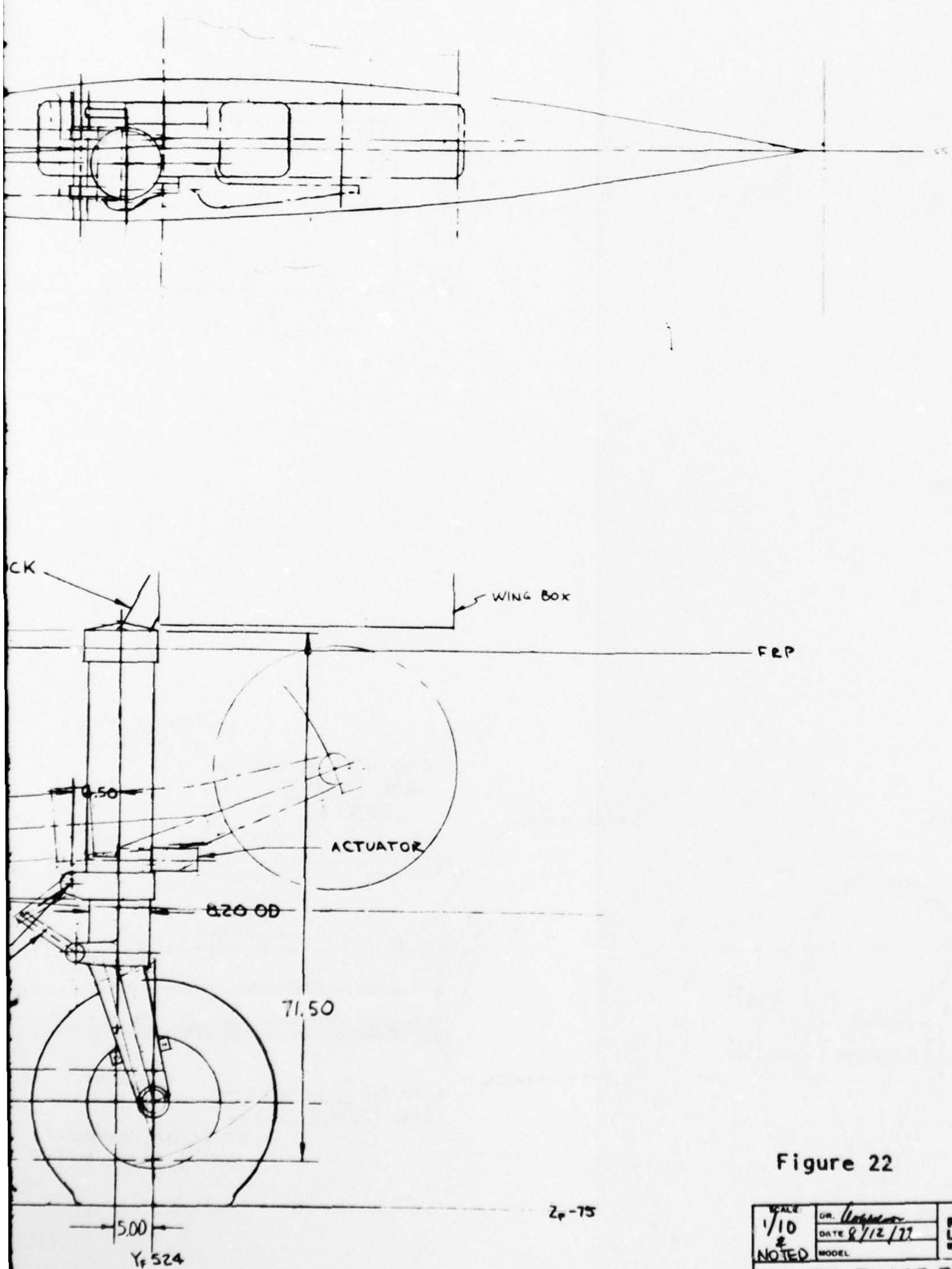


Figure 22

SCALE 1/10 & NOTED	DR. DATE 8/12/77 MODEL	Rockwell International Corporation Los Angeles Aircraft Division INTERNATIONAL AIRPORT LOS ANGELES, CALIFORNIA	ADVANCED DESIGN
STUDY - PHASE II ATS MAIN LANDING GEAR METAL MATRIX COMPOSITE CONCEPT E			D619-1-412 SHEET 1 OF 2

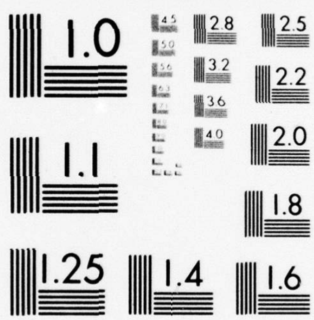
FORM AP-60-E-36 REV 7-76

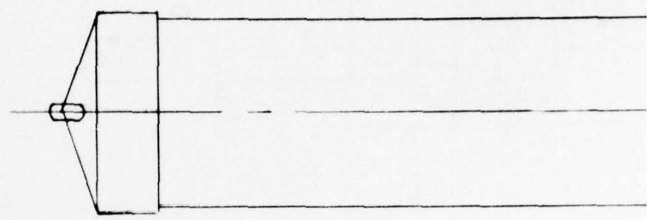
AD-A058 529 ROCKWELL INTERNATIONAL LOS ANGELES CA LOS ANGELES DIV F/G 11/4
NEW CONCEPTS IN COMPOSITE MATERIAL LANDING GEAR FOR MILITARY AI--ETC(U)
FEB 78 V E WILSON F33615-76-C-3021

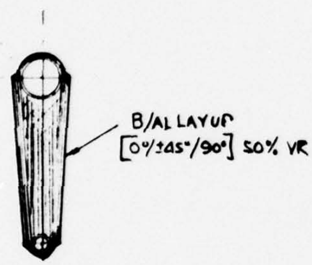
UNCLASSIFIED AFFDL-TR-78-2-VOL-1 NL

2 OF 2
AD
A058529

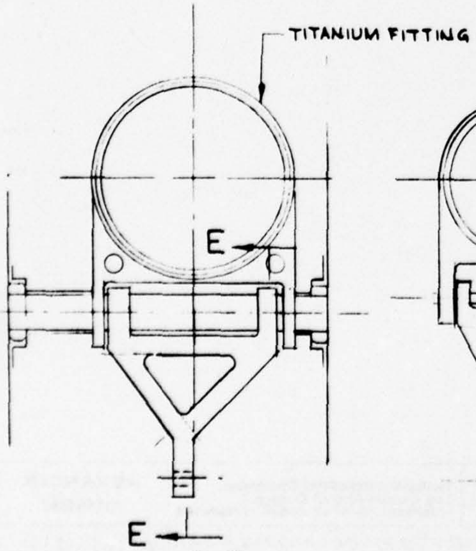
END
DATE
FILMED
11-78
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

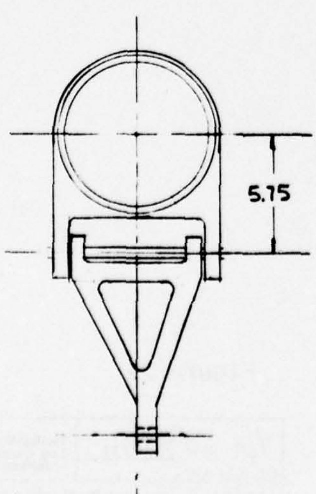




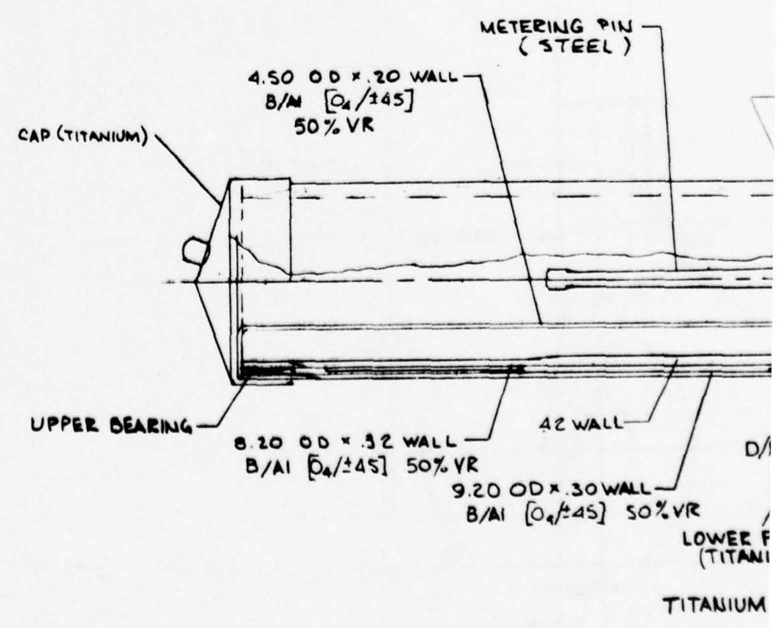
SEC E-E



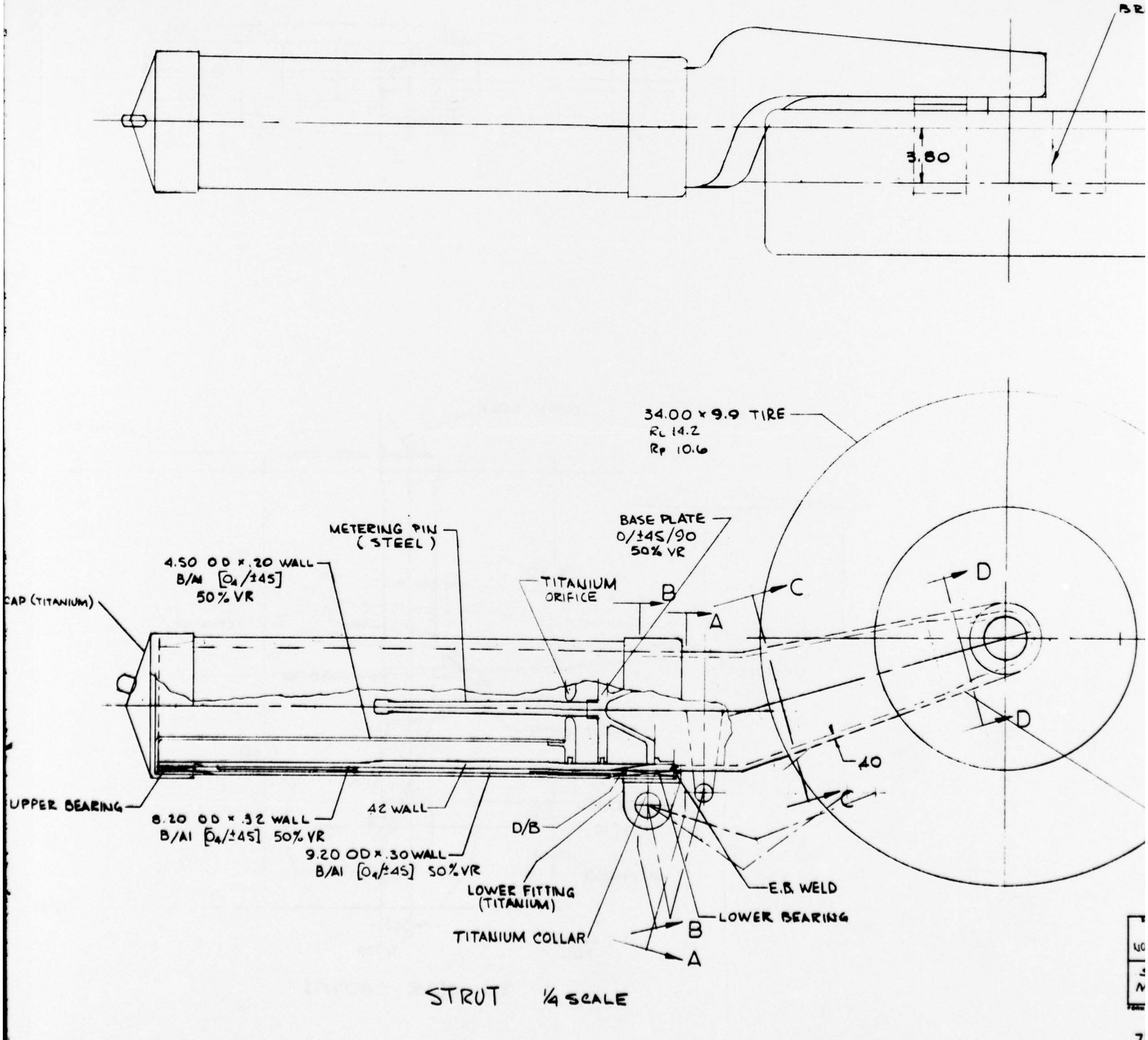
SEC BB



SEC AA



STRUT



STRUT 1/4 SCALE

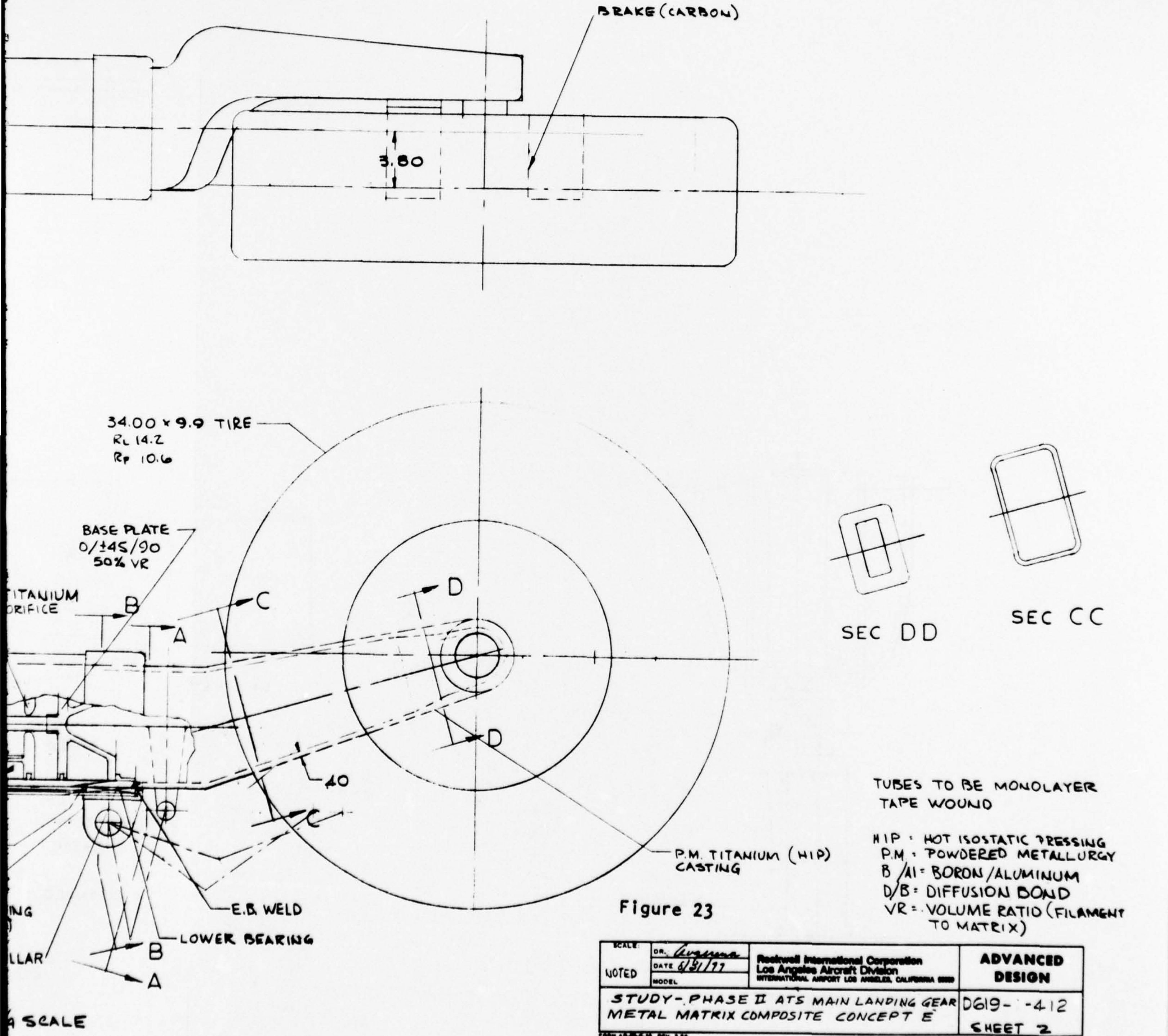

BRAKE (CARBON)
3.80
34.00 x 9.9 TIRE
RL 14.2
Rp 10.6
BASE PLATE
0/±45/90
50% VR
TITANIUM
ORIFICE
B
A
C
D
D
C
40
SEC DD
SEC CC
TUBES TO BE MONOLAYER
TAPE WOUND
HIP = HOT ISOSTATIC PRESSING
P.M. = POWDERED METALLURGY
B/Al = BORON/ALUMINUM
D/B = DIFFUSION BOND
VR = VOLUME RATIO (FILAMENT TO MATRIX)
P.M. TITANIUM (HIP) CASTING
E.B. WELD
LOWER BEARING
ING
LLAR
B
A
A SCALE
SCALE NOTED
DR. Averna
DATE 6/31/77
MODEL
Rockwell International Corporation
Los Angeles Aircraft Division
INTERNATIONAL AIRPORT LOS ANGELES, CALIFORNIA
ADVANCED DESIGN
STUDY - PHASE II ATS MAIN LANDING GEAR
METAL MATRIX COMPOSITE CONCEPT E
D619- -412
SHEET 2

Figure 23

3

The forward trunnion locations on Concepts B, C, and D require resizing nacelle structure in that area, while Concept E has the trunnion in the same location as the baseline concept. Both Concept C and D require the duct splitter to be widened by six inches over the baseline, while Concept E requires only one inch extra. Duct and nacelle changes will increase both the frontal area of the aircraft, and its weight. These changes also increase cost, so Concept E is estimated to be the lowest cost configuration.

Fabrication of the components on any of the configurations will be very difficult and would require an extensive manufacturing and tooling process development program prior to fabrication of any parts.

From the evaluation given above and summarized in table XXIII, Concept E, the conventional landing gear configuration, has been selected as the best configuration for the metal matrix composite, and will be used in the evaluation against the best organic composite concept and the best advanced metallic concept.

4.2.3 Advanced Metallic System

Superplastic formed and diffusion bonded (SPF/DB) titanium has been selected as the advanced metallic system to be investigated in this study. This material has an outstanding strength-to-density ratio and resistance to corrosion. The SPF/DB process will be used to fabricate complex landing gear parts at lower costs.

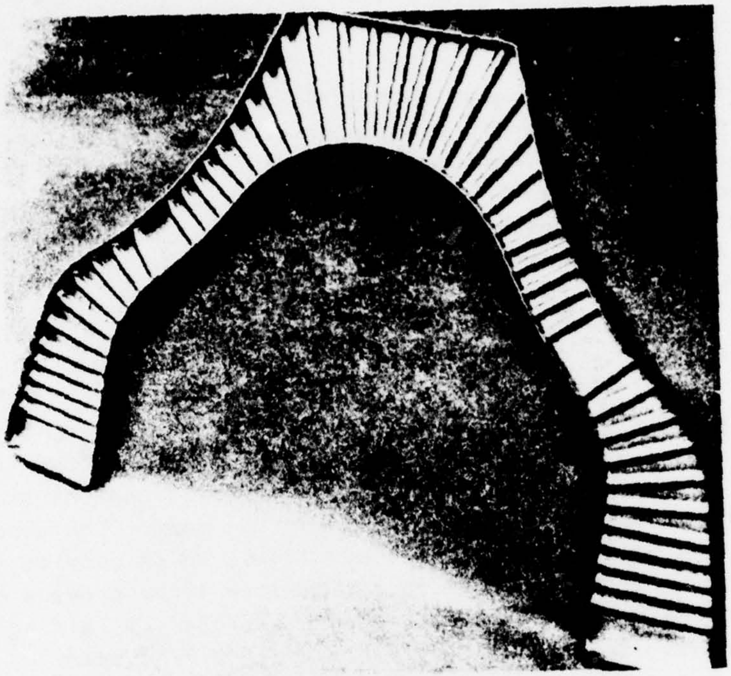
The basis for the SPF/DB process is the superplasticity and diffusion bonding properties of titanium.

Superplasticity in titanium is a phenomenon in which very large tensile elongations may be realized because local thinning (necking) does not occur under the proper conditions of temperature and strain rate. Diffusion bonding is the joining of titanium under pressure at elevated temperature without melting or use of bonding agents. Fortunately, through a natural occurrence, superplastic forming and diffusion bonding of titanium can be accomplished under identical parametric conditions. This allows the superplastic forming and diffusion bonding of titanium to take place concurrently within the die cavity. Many structural forms are possible, including sandwich structures made by expanding face sheets and core against die forms. The classic difficulties normally associated with fabricating sandwich structures, such as parts fit-up, close tolerances, adhesive or braze alloy strength, do not exist with this technique. Examples of parts made using this SPF/DB process are shown in figure 24.

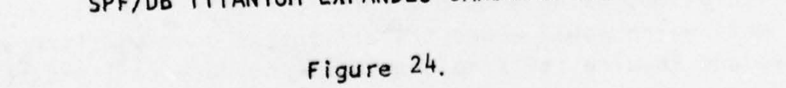
TABLE XXIII

EVALUATION - METALLIC MATRIX COMPOSITE CONCEPTS

CONCEPT	KINEMATICS	MAJOR PARTS	FAB-RICATION	WEIGHT	NACELLE STRUCTURE REVISIONS	COST ESTIMATE
A	Superior	Fwd Drag Links (2) Aft Drag Link Lock Piston Cylinder	Difficult	Heavy	Very Extensive	Not a Viable Concept
B	Superior	Fwd Drag Link Aft Drag Link Lock Piston-Fork Cylinder	Difficult	Heavy	Extensive	Very High
C	Superior	Drag Link Piston Cylinder Retracting Links(2) Lock	Difficult	Heavy	Major	High
D	Superior	Trailing Beam Piston Cylinder Retracting Links(2) Lock	Difficult	Heaviest	Major	High
E	Adequate	Piston-Fork Cylinder Torque Links(2) Lock	Difficult	Lightest	Minor	Lowest



SPF/DB TITANIUM NACELLE FRAME



TRUSS CORE

SPF/DB TITANIUM EXPANDED SANDWICH HARDWARE

Figure 24.

Three different landing gear configurations were studied to determine which one could most efficiently use component parts fabricated from SPF/DB titanium. Studies were a "trailing arm" concept, a "four bar linkage" concept and a "conventional landing gear" concept. Each of these concepts has advantages and disadvantages and require different types of component parts. Each concept will be discussed separately and then subjectively evaluated to determine which advanced metallic concept is best and should be selected for comparison to the best of the organic advanced composite and metal matrix composite concepts.

4.2.3.1 Trailing Arm Concept. A titanium landing gear using a trailing arm configuration is shown in figure 25. The wheel is mounted in a double fork at the aft end of a beam which is supported by trunnions at the forward end and the shock absorber near the center of the beam. The shock absorber is fastened to the upper link and two lock links, which provide the retraction and locking mechanism for this concept. The lock links provide over-center locking in both the extended and retracted positions. A fairing or partial wheel well door has been incorporated into the trailing beam.

The kinematics of this system result in a wheel motion, at impact, that is advantageous for absorbing spinup loads and would reduce spring back loads. This system would not have the advantage of emergency unpowered free fall to a locked extended position. The double fork holding the wheel will require a special anti-skid sensor installation and will make wheel and tire removal more complicated.

Vertical and fore and aft loads result in bending of the trailing beam and are reacted at the forward trunnion and the shock absorber. The side loads result in side bending and torsion in the trailing beam and are reacted at the forward trunnions only. The lock links are lightly loaded since they only serve to hold the upper link and the shock absorber "on-center". The upper link is highly loaded in compression since it must react the full shock absorber landing impact loads. The trailing beam, the upper link and the lock links will all be fabricated from titanium using the SPF/DB process. The shock absorbers used in compression in this configuration is a "Liquid Spring," which is smaller and lighter than the air-oil type. The "Liquid Spring" is a very high pressure cylinder which absorbs energy by metering oil through an orifice, and for a spring, compresses a closed volume of special oil rather than using the air "spring" which is used in the air-oil shock absorber. The "Liquid Spring" cylinder will be machined from 300M steel.

This configuration, using a double fork to hold the wheel, will require a wider wheel well which would widen the air intake duct splitter approximately 3 inches and require revising both duct and nacelle lines to retain

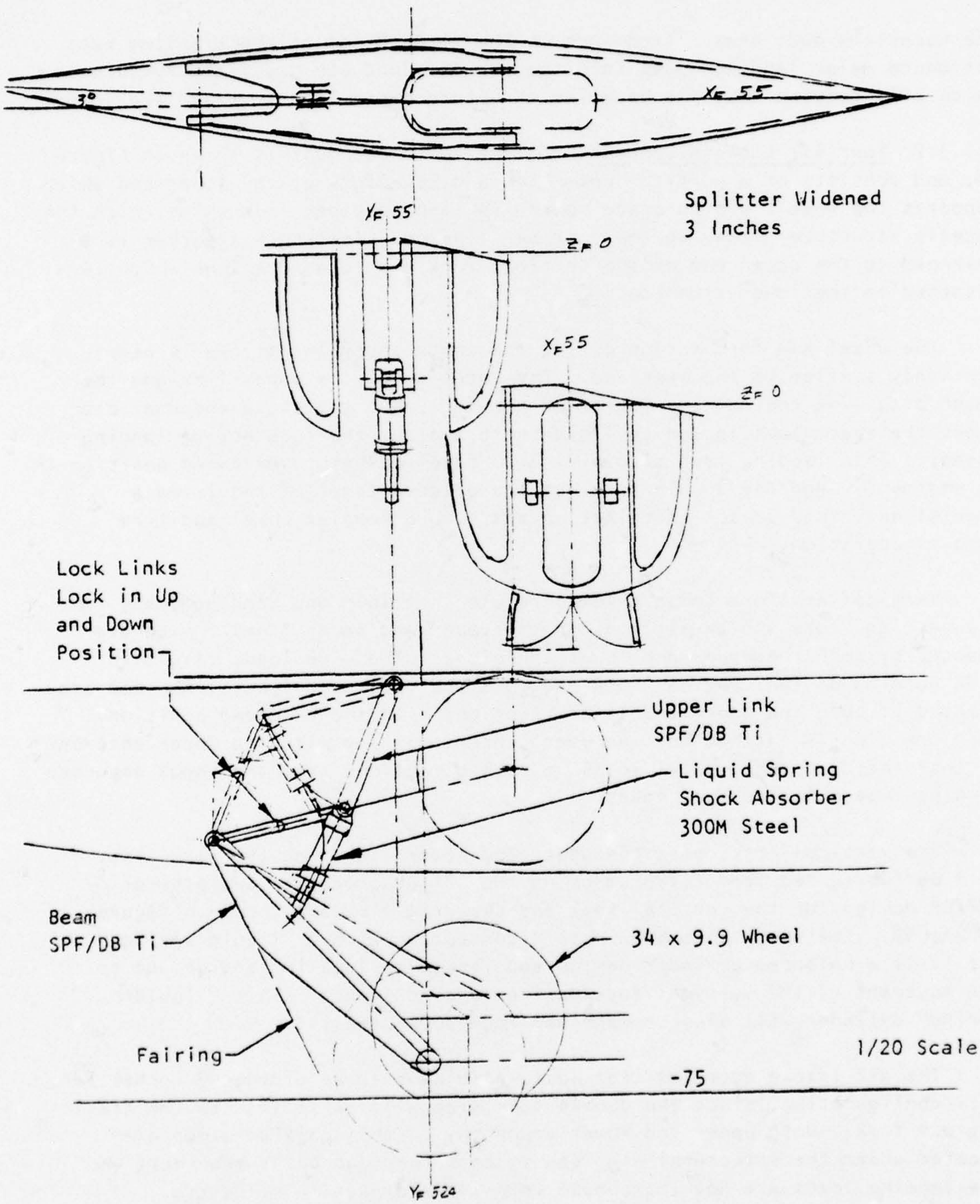


Figure 25. Trailing Arm Configuration (SPF/DB Titanium)

the necessary duct area. Trunnions at the forward end of the trailing beam introduce major landing loads into the forward duct and nacelle structure, which will require that the baseline structure be resized to react the loads.

4.2.3.2 Four Bar Linkage Concept. This titanium concept is shown in figure 26, and consists of a vertical beam with a double fork at the lower end which supports the wheel, a drag brace lower link and an upper link which, with the nacelle structure, makes up the four bar linkage. The shock absorber is fastened to the upper end of the vertical fork and to a lock link which is attached to the lower trunnion.

The wheel and fork motion during the shock absorbing stroke is nearly vertical, similar to the baseline. The rotation of the upper link and the lower drag link control the motion of the fork, and the shock absorber provides the energy absorption to limit the travel of the fork during landing impact. This landing gear also will not "free fall" into extended position in an emergency, and the double fork has the disadvantages of requiring a special anti-skid sensor installation and a more complex wheel and tire removal operation.

Vertical and fore and aft loads result in column and bending loads in the vertical fork and axial loads in the upper and lower links, which are reacted by both the upper and lower trunnions. The side loads result in side bending on the vertical fork and both the upper and lower links and are reacted at both the upper and lower trunnions. In the extended position, the lock link is latched into an over center position with the shock absorber so that they can react axial loads in both directions from the shock absorber landing impact and rebound loads.

The vertical fork, both the upper and lower links and the lock link, will be fabricated from titanium using the SPF/DB process. Examples of SPF/DB design for the vertical fork and the drag link are shown in figures 27 and 28. The shock absorber in this concept is also a "liquid spring," but it is a balanced cylinder design and its major load is tension due to the movement of the vertical fork during landing impact. This "liquid spring" cylinder will also be machined from 300M steel.

The air intake duct splitter would also have to be widened 3 inches for this configuration, since the double fork size will be similar to the trailing arm fork. Both upper and lower trunnions in this configuration are located under the structural wing box so that the load paths are short and the landing loads are not introduced into forward nacelle structure.

4.2.3.3 Conventional Landing Gear Concept. A conceptual study of a conventional landing gear using titanium with the shock strut as the main structural

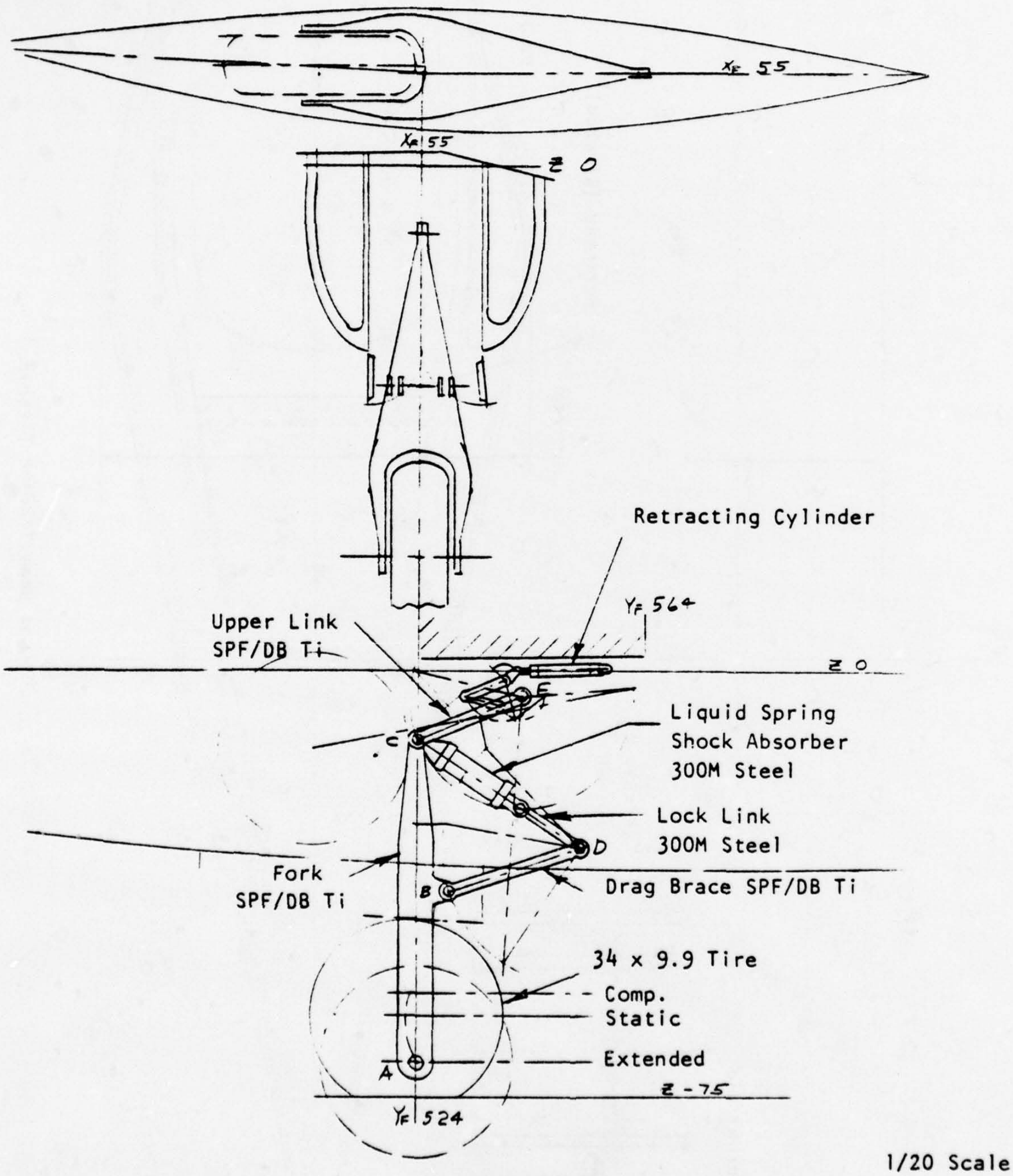


Figure 26. Four Bar Linkage Concept (SPF/DB Titanium)

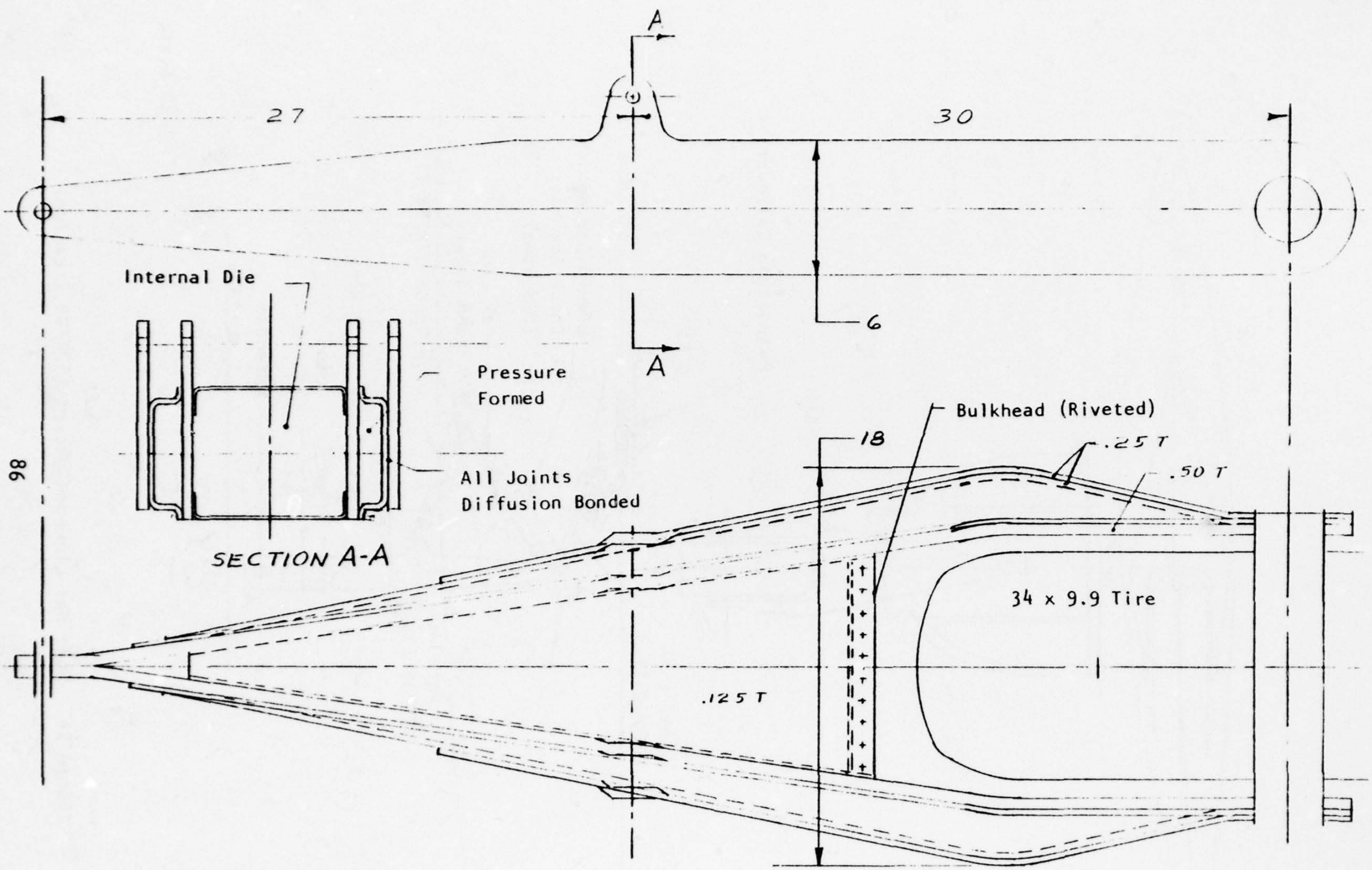


Figure 27. Vertical Beam (SPF/DB Titanium)

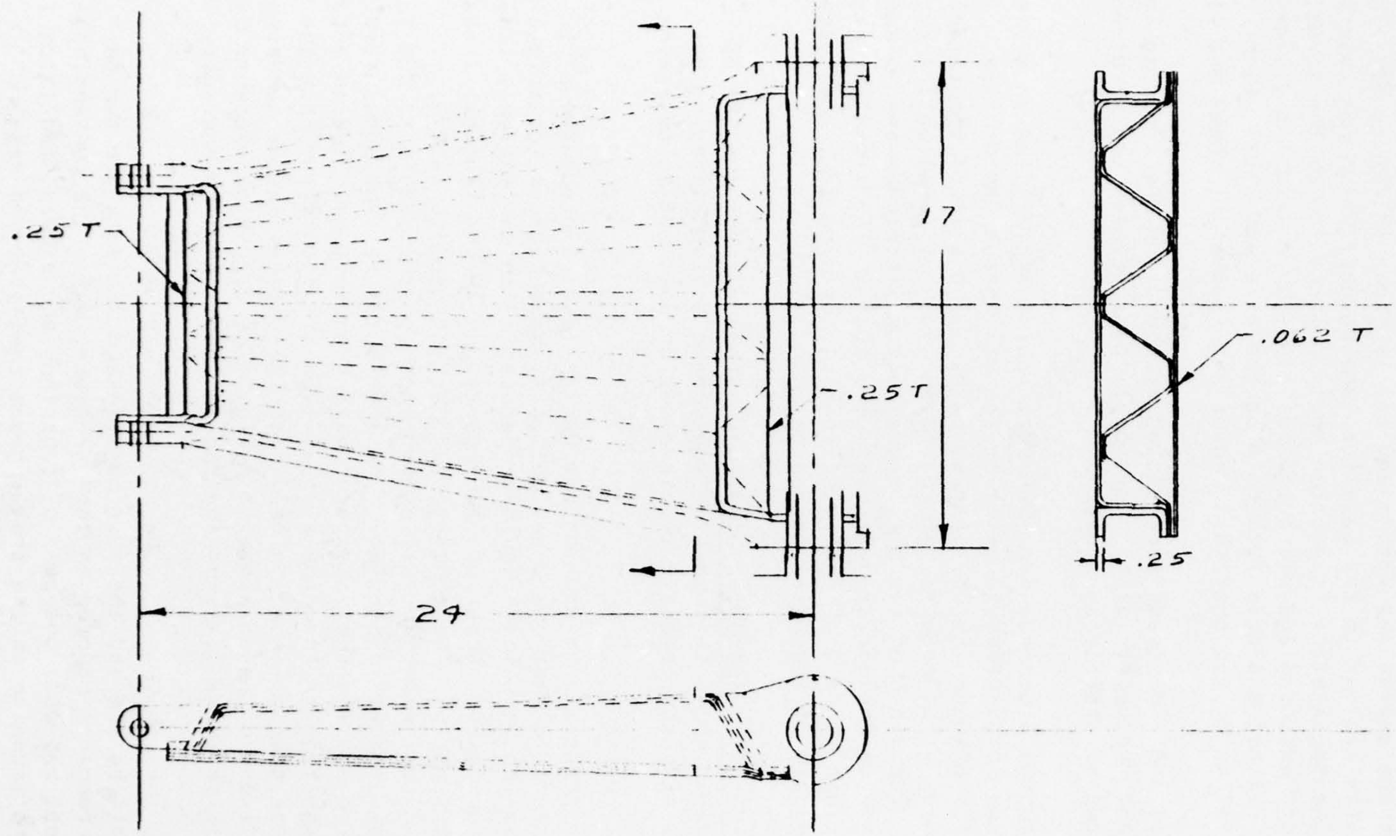


Figure 28. Drag Link (SPF/DB Titanium)

member, as well as the energy absorption device, is shown in figure 29. This landing gear is quite similar to the baseline landing gear which was cescribed in Section III. The shock strut is mounted on trunnions, low on the strut, and locked into both extended and retracted positions by a latching device on top of the strut. It has a single fork holding the axle and wheel which simplifies installation of the anti-skid sensor and removal of wheel and tires.

Vertical loads and side loads are reacted by the trunnions and drag loads by the trunnions and the upper latch. Torsional loads between the strut and the fork are reacted by the torque links.

The shock strut will be made from SPF/DB titanium and will be an air-oil type in which energy is absorbed by metering the oil through an orifice. The fork and wheels will also be SPF/DB titanium parts. The size of the titanium single fork and shock strut requires an increased width of wheel well to stow the landing gear. The width of the air intake duct splitter has been widened to 19 inches to provide the additional wheel well space. The trunnions are located under and just forward of the front spar of the wing box, thus retaining the short load path of the baseline design.

4.2.3.4 Advanced Metallic Concept Evaluation. Since each of the SPF/DB titanium concepts studied in this section would make a viable landing gear system for the ATS airplane, a subjective evaluation was made to determine the best concept.

Kinematics of the trailing arm concept during landing are superior to the other two concepts in that the wheel motion is advantageous for absorbing spinup loads and spring back loads would be reduced. The conventional landing gear concept has the fewest number of major parts, while the four bar linkage concept has the most parts. The conventional landing gear concept is estimated to be lightest and the trailing beam concept the heaviest, due to the long beam highly loaded in bending. The liquid spring type shock struts used in the trailing arm and the four bar linkage concepts have the advantage of being smaller and lighter than the air-oil type of shock strut, but the static height of the gear will vary widely with the changes in the temperature of the special silicone oil used as strut fluid. The very high pressure used in these units require super finishes and special sealing which increases the cost.

Both the trailing arm and the four bar linkage concepts use two pair of highly loaded trunnions mounted on the structure, while the conventional landing gear concept has only one pair of trunnions and a drag load latch mount. The forward trunnion on the trailing arm concept would require resizing structure in the forward nacelle, while both other concepts have the

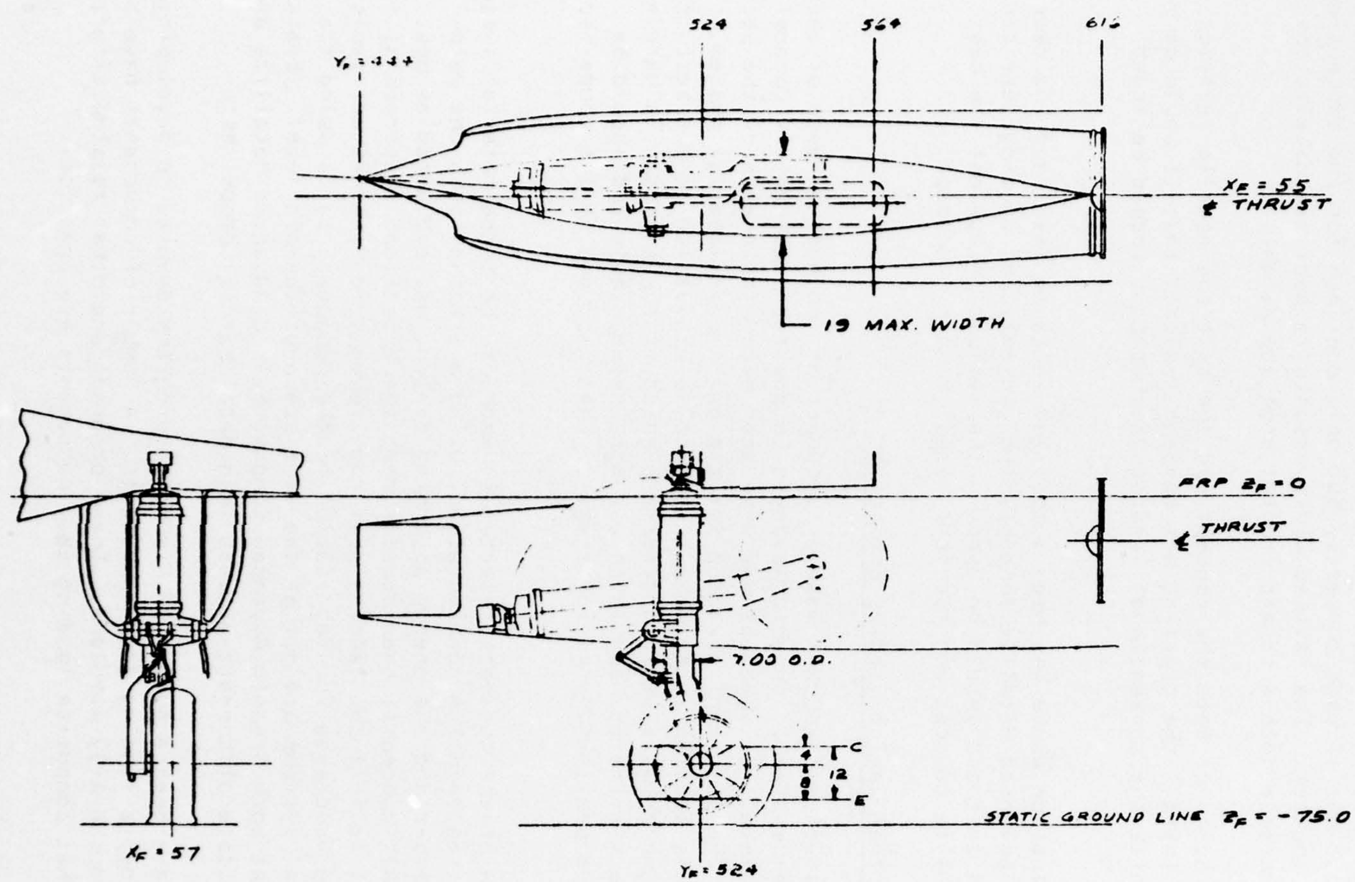


Figure 29. Conventional Landing Gear Concept (SPF/DB Titanium)

trunnions under the structural wing box. The width of the air intake duct splitter must be increased three inches to accommodate either the trailing arm or the four bar linkage concepts, but only one inch for the conventional landing gear concept. The revised width results in duct and nacelle changes which will increase both aircraft frontal area and weight.

Consideration of both the concept and the duct and nacelle revisions necessary to install the trailing arm concept indicate that it would be most expensive, while the conventional landing gear concept should be least expensive.

The evaluation above has been summarized in table XXIV, and indicates that for the advanced metallic concept, the conventional landing gear configuration is best and should be used in the evaluation against the best organic composite concept and the best metallic matrix concept.

4.2.4 Conceptual Design Studies Evaluation

Design studies have been made of a number of concepts in each of the three material systems: Organic Advanced Composite, Metal Matrix Composite and Advanced Metallic. Evaluations have been made within each of the sections to determine the best configuration for the particular material system. The purpose of this section is to make a subjective evaluation of the best concept of each material system to determine which of the concepts is marginal and should be eliminated, and which are considered viable and should be carried to the preliminary design stage so that cost and weight comparisons can be made.

A review of the concepts selected in each of the three material systems reveals that the baseline configuration, using a strut as both the main structural member and the energy absorbing device, was evaluated as best in each case. All concepts, then equally meet the "function" constraints; that is, each will fulfill the landing gear requirements for the ATS air vehicle. Manufacturing processes for fabrication of the component parts using the three material systems are not at the same state-of-the-art level. Evaluation indicates that both Organic Advanced Composites and Advanced Metallics are closer to a state-of-the-art process than Metal Matrix Composites.

There have been a number of Air Force programs devoted to developing organic composite landing gear components. A number of components have been developed for the A-37 airplane. These programs and other related efforts have shown that composite landing gear components are practical.

TABLE XXIV

EVALUATION - ADVANCED METALLICS CONCEPTS

SPF/DB TITANIUM

CONCEPT	KINEMATICS	MAJOR PARTS	WEIGHT ESTIMATE	SHOCK STRUT	NACELLE STRUCTURE REVISIONS	COST ESTIMATE
Trailing Arm	Superior	Beam-Fork Piston Cylinder Upper Link Lower Lock Link Upper Lock Link	Heaviest	Liquid Spring Adequate	Major	Highest
Four Bar Linkage	Adequate	Vertical Fork Upper Link Lower Link Lock Link Piston Cylinder Actuator Link	Moderate	Liquid Spring Adequate	Moderate	Moderate
Conventional Landing Gear	Adequate	Piston-Fork Cylinder-Strut Upper Torque Link Lower Torque Link Latch	Lightest	Air-Oil Type Superior	Minor	Lowest

The Advanced Metallic material system using SPF/DB titanium has been proven to have both cost and weight saving advantages. The design advantages and manufacturing feasibility of this technology has been established by a number of Rockwell IR&D programs and Air Force and NASA contracts.

An extensive literature survey has been made to discover other metal matrix applications and to see how the tooling and production complexities of metal matrix composite fabrication have been solved. It is fairly evident that with the exception of engine blades and thin walled tube structure, little or no fabrication experience with complex metal matrix parts exists.

The major structural components to be made from boron/aluminum in this program are the strut cylinder and the piston. These parts are heavy walled cylinders subjected to axial, bending and internal pressure loads. Cross plied lamiate orientations must be used to give multi-axial load carrying capability.

While tube structures of boron/aluminum have been successfully fabricated in production for space shuttle strut applications, these tubes were thin walled structures, relatively lightly axially loaded. These tubes were made using unidirectional (0° orientation) tape with relatively few plies thickness and only 3.4 inches in diameter. The tubes required for the strut and piston for this concept must be laid up with cross ply orientations of $\pm$ 45° and 90° as well as the 0° axial orientation to accommodate the multi-axial stress state. They must be up to 108 plies thick and 9.2 inches outside diameter.

This then produces a very high risk producibility problem. While the same tooling concept of sacrificial tooling appears attractive for thick wall tube fabrication, several major processing problems become apparent. First, the thick wall thermal coefficient of expansion problem must be solved. Through trial and error this tolerance could be provided for in the outer hard tool. The second problem, however, is not as easily overcome. When the inner expandable tooling mandrel expands from internal pressure, it forces the radial and off-axis oriented fibers to effectively "stretch" to meet the outer larger radius as the matrix becomes molten and consolidation takes place. This would produce parts with one, possibly two, intrinsic characteristics which would be very undesirable from a designers standpoint.

If the fibers could "stretch" radially, this would either cause a preload on the fiber, cause fiber breakage or yield fiber separation as the mylar pattern ply is forced to wrap over a larger diameter than it was fabricated for.

More realistically, assuming these high strength fibers do not stretch to provide the radial displacement required for consolidation, the matrix

would effectively move through fibers towards the outer diameter as the inner tool expands. This would yield very high fiber volume fractions on the inner surface and moderate to low on the outer. A mix of properties through the thickness of the part would result, and since this would not correlate with an established data base of material properties, a further risk factor is introduced which must be considered in this evaluation.

It may therefore be concluded that boron/aluminum fabrication, while possibly the best characterized of the Metal Matrix composite systems, is not a state-of-the-art technology. A substantial amount of manufacturing process and tooling development will be required before it may be considered so.

Due to the very high producibility risk involved in the fabrication of complex Metal Matrix component parts, it is concluded that this material is, at the present time, marginal, and should be excluded from further design effort in this program. The two material systems selected for preliminary design studies and analysis are the Organic Advanced Composite System and the Advanced Metallic System. Table XXV summarizes the comparison between the three material systems.

4.3 PHASE II PRELIMINARY DESIGN STUDIES

The conceptual designs of the organic composite and the advanced metallic material systems which were described and selected earlier in this section, have been refined to a preliminary design stage from which a cost and weight analysis will be made.

4.3.1 Organic Composite Preliminary Design

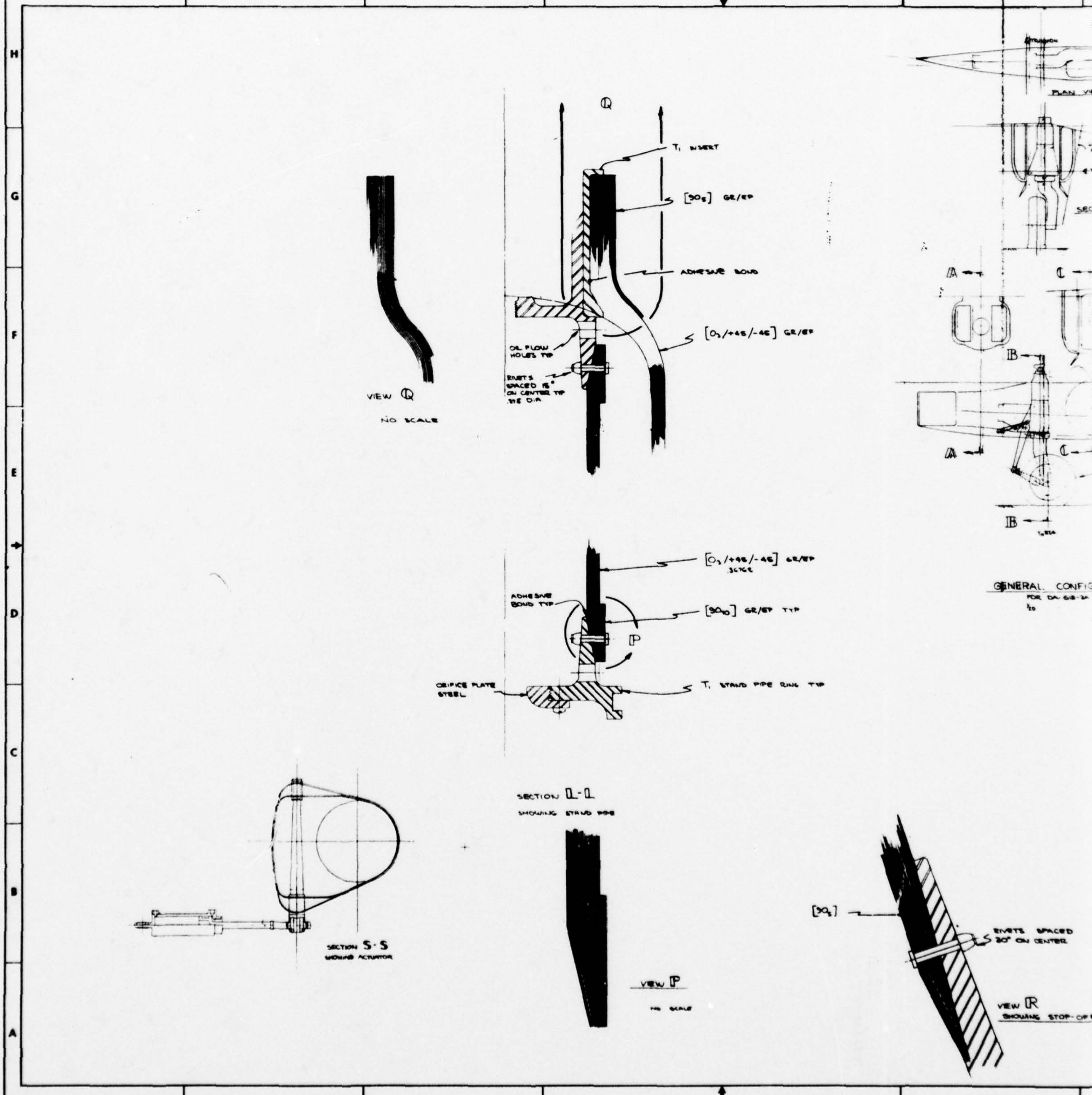
The conventional landing gear configuration was selected as the best organic composite conceptual design earlier in this section. A preliminary design, figure 30, has been made using this concept. This configuration uses the shock strut as the main structural member similar to the baseline design. The parts of this design to be fabricated from organic composite material (Gr/Ep) will be the shock strut cylinder, trunnion support, orifice support tube, piston/fork, inner piston shell, upper and lower torque links and the wheel.

To facilitate the preliminary design and analysis of these multi-axial loaded members, the composite laminate used was ($0^\circ_3 \pm 45^\circ$) orientation. In a final design the orientations would be further optimized for "layup" fabrication or changed to facilitate "filament winding" operations, but for the scope of this study, satisfactory weight and cost estimates can be obtained by using ($0^\circ_3 \pm 45^\circ$) laminate.

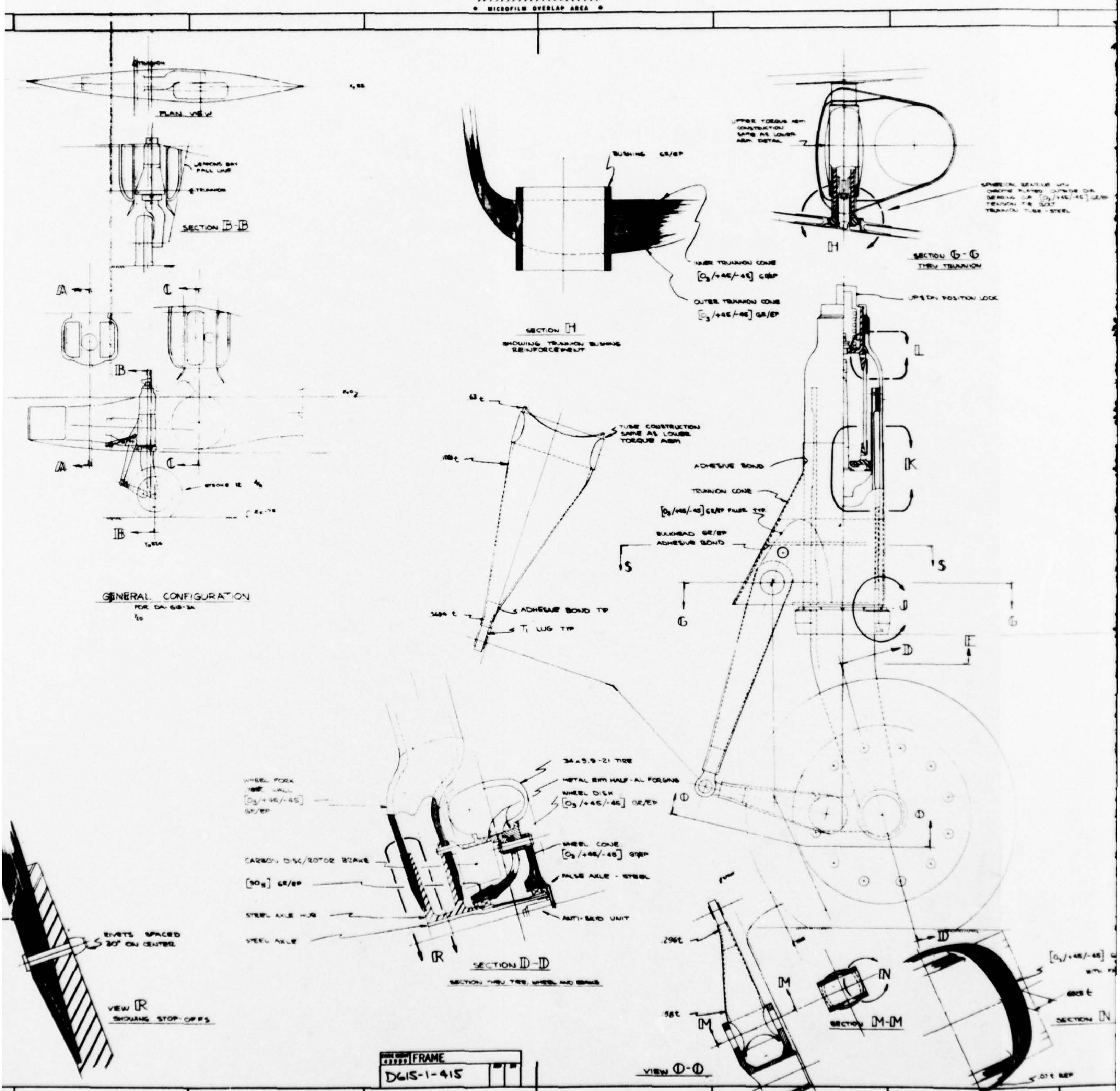
TABLE XXV

EVALUATION - THREE MATERIAL SYSTEMS - DESIGN CONCEPTS

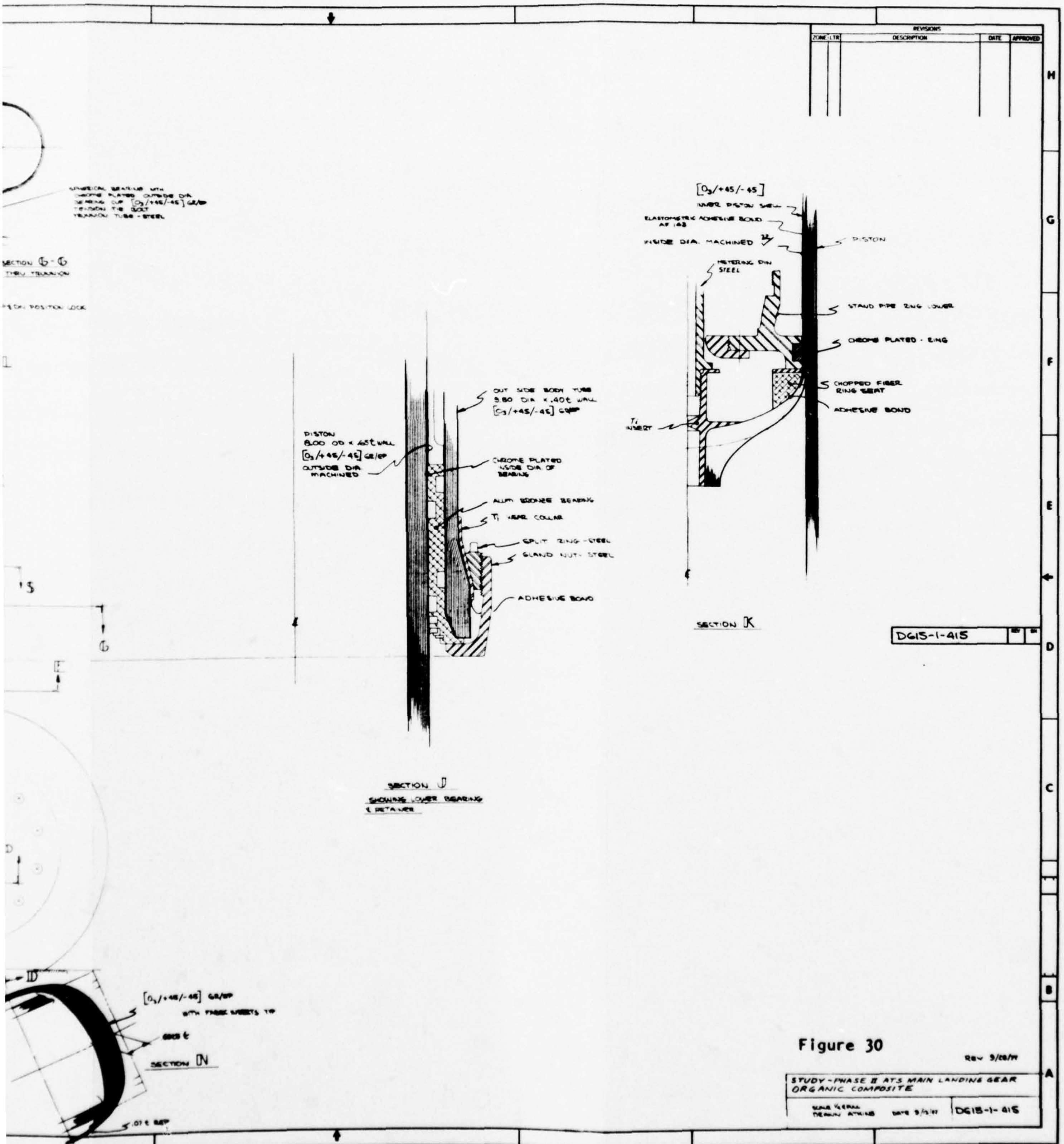
MATERIAL SYSTEM	CONCEPT	MATERIAL	NACELLE STRUCTURE REVISIONS	DEVELOPMENT PROGRAM REQUIREMENTS	PRODUCIBILITY RISK	RECOMMENDATIONS
Organic Advanced Composite	Conventional Landing Gear	Gr/Ep Laminate	Moderate	Moderate	Moderate	Continue Design Effort
Metal Matrix Composite	Conventional Landing Gear	B/Al Diffusion Bonded	Minor	Extensive	Very High	Stop Design Effort
Advanced Metallics	Conventional Landing Gear	Titanium SPF/DB	Minor	Moderate	Moderate	Continue Design Effort



H
G
F
E
D
C
B
A
Q
T_i INSERT
[90_5] GR/EP
ADHESIVE BOND
[0_3/+45/-45] GR/EP
OIL FLOW HOLES TYP
RIVETS SPACED 15" ON CENTER TYP .375 DIA
VIEW Q
NO SCALE
[0_3/+45/-45] GR/EP
ADHESIVE BOND TYP
[90_{10}] GR/EP TYP
P
ORIFICE PLATE STEEL
T_i STAND PIPE RING TYP
SECTION L-L
SHOWING STAND PIPE
SECTION S-S
SHOWING ACTUATOR
VIEW P
NO SCALE
[90_5]
RIVETS SPACED 30" ON CENTER
VIEW R
SHOWING STOP-OFF
PLAN VIEW
A
B
C
GENERAL CONFIG
FOR DA-618-3A


MICROFILM OVERLAP AREA
PLAN VIEW
SECTION B-B
GENERAL CONFIGURATION
FOR DA-68-3A
BUSHING GR/EP
INNER TRUNNION CONE
[O3/+45/-45] GR/EP
OUTER TRUNNION CONE
[O3/+45/-45] GR/EP
SECTION H
SHOWING TRUNNION BUSHING REINFORCEMENT
TUBE CONSTRUCTION SAME AS LOWER TORQUE ARM
ADHESIVE BOND TYP
Ti LUG TYP
SECTION G-G
THRU TRUNNION
UP & DN POSITION LOCK
ADHESIVE BOND
TRUNNION CONE
BULKHEAD GR/EP
ADHESIVE BOND
34 x 9.9-21 TIRE
METAL RIM HALF-AL FORGING
WHEEL DISK
[O3/+45/-45] GR/EP
WHEEL FORK
WHEEL CONE
[O3/+45/-45] GR/EP
CARBON DISC/ROTOR BRAKE
[90s] GR/EP
FALSE AXLE - STEEL
STEEL AXLE HUB
ANTI-SKID UNIT
STEEL AXLE
SECTION D-D
SECTION THRU TIRE, WHEEL AND BRAKE
RIVETS SPACED 30° ON CENTER
VIEW R
SHOWING STOP-OFFS
VIEW D-D
SECTION M-M
SECTION N
FRAME
D615-1-415

2



REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
SECTION G - G
THRU TRUNNION
[O3/+45/-45]
INNER PISTON SHELL
ELASTOMETRIC ADHESIVE BOND
AF 143
INSIDE DIA. MACHINED
PISTON
METERING PIN
STEEL
STAND PIPE RING LOWER
CHROME PLATED - RING
CHOPPED FIBER
RING SEAT
ADHESIVE BOND
Ti
INSERT
OUT SIDE BODY TUBE
9.80 DIA x .40t WALL
[O3/+45/-45] GR/EP
PISTON
8.00 OD x .65t WALL
[O3/+45/-45] GR/EP
OUTSIDE DIA
MACHINED
CHROME PLATED
INSIDE DIA OF
BEARING
ALUM BRONZE BEARING
Ti WEAR COLLAR
SPLIT RING - STEEL
GLAND NUT - STEEL
ADHESIVE BOND
SECTION K
SECTION J
SHOWING LOWER BEARING
& RETAINER
D615-1-415
[O3/+45/-45] GR/EP
WITH FABRIC SHEETS TYP
SECTION N
REV 9/20/77
STUDY - PHASE II ATS MAIN LANDING GEAR
ORGANIC COMPOSITE
DRAWN ATKINS
D615-1-415

Figure 30

5

This notation ($0^\circ_3 \pm 45^\circ$) denotes a five layer laminate having a top axial ply (0°), a 45° (to axial) ply, a center axial ply, a 45° ply (90° to other 45° ply) and a bottom axial ply. Multiples of two laminates are used to achieve the required thickness.

4.3.1.1 Shock Strut Cylinder. The shock strut cylinder is a pressure vessel which is also subjected to both axial and bending loads. The loads are reacted at the trunnion and at the upper latch. The trunnion support is separate and is adhesive bonded to the strut. The latch is mechanically fastened to the strut by the threaded upper end cap. The shock strut will be 9.8 inches outside diameter compared to 5.8 inches for the baseline metallic landing gear. This was done to increase the cross section of the composite cylinder to compensate for the decreased properties of the composite when compared to the high strength steel of the baseline design.

The strut cylinder will be fabricated by filament winding on a metal mandrel which will make two parts at once. The upper necked end with the titanium insert will be fastened to each end of the mandrel. After cure the two strut cylinders will be cut apart at the thicker, interleaved, lower end ring at the center of the mandrel. The inside of the cylinder, which was cured against the ground finish of the mandrel, will not need to be machined. The outer surface, however, will have to be machined to provide an accurate surface for bonding to the trunnion support cone and to the titanium wear collar. See figure 31.

4.3.1.2 Trunnion Support. The trunnion support is a cone shaped composite part which is bonded to the lower end of the shock strut and provides support for the trunnion pin, the upper torque link and the mounting pin for the strut extend/retract actuator. This support configuration was selected because it more efficiently uses the excellent two dimensional properties of composites than lug type designs.

Two trunnion supports will be filament wound at once on a metal mandrel. The larger end of each part will be in the center of the mandrel. The trunnion pin area of the part will be reinforced by a laminated Gr/Ep insert. This insert will be separately laid up and cured in a matched metal mold to final dimensions. The inner trunnion support cone will be filament wound onto the mandrel, the two inserts will be placed in position and the outer trunnion support cone filament wound over the inner cone and inserts. After cure, the two trunnion support cones will be cut apart and removed from the mandrel. The trunnion support will be machined on the inside only in the area to be bonded to the strut cylinder. See figure 32.

The titanium wear collar will be adhesive bonded to the lower end ring of the cylinder and then the trunnion support cone will be positioned and adhesive bonded to the strut cylinder. Separately cured Gr/Ep bulkheads will be adhesive bonded to both strut cylinder and trunnion support cone. The

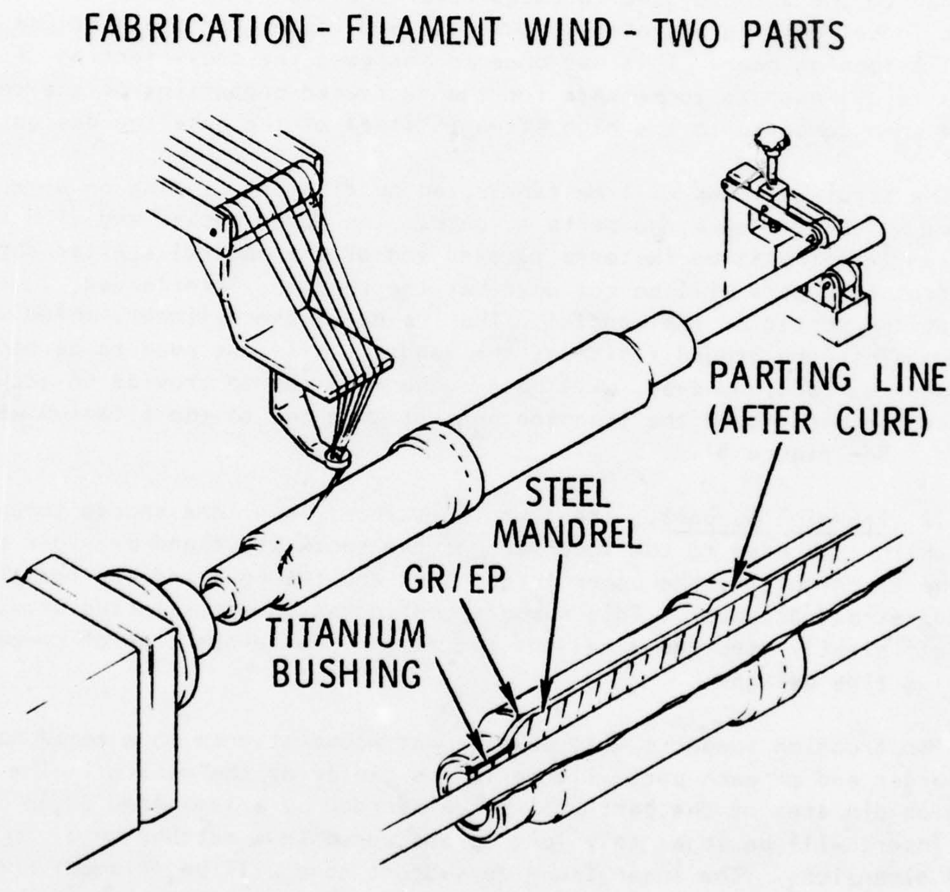


Figure 31. Strut Cylinder Filament Winding Tooling

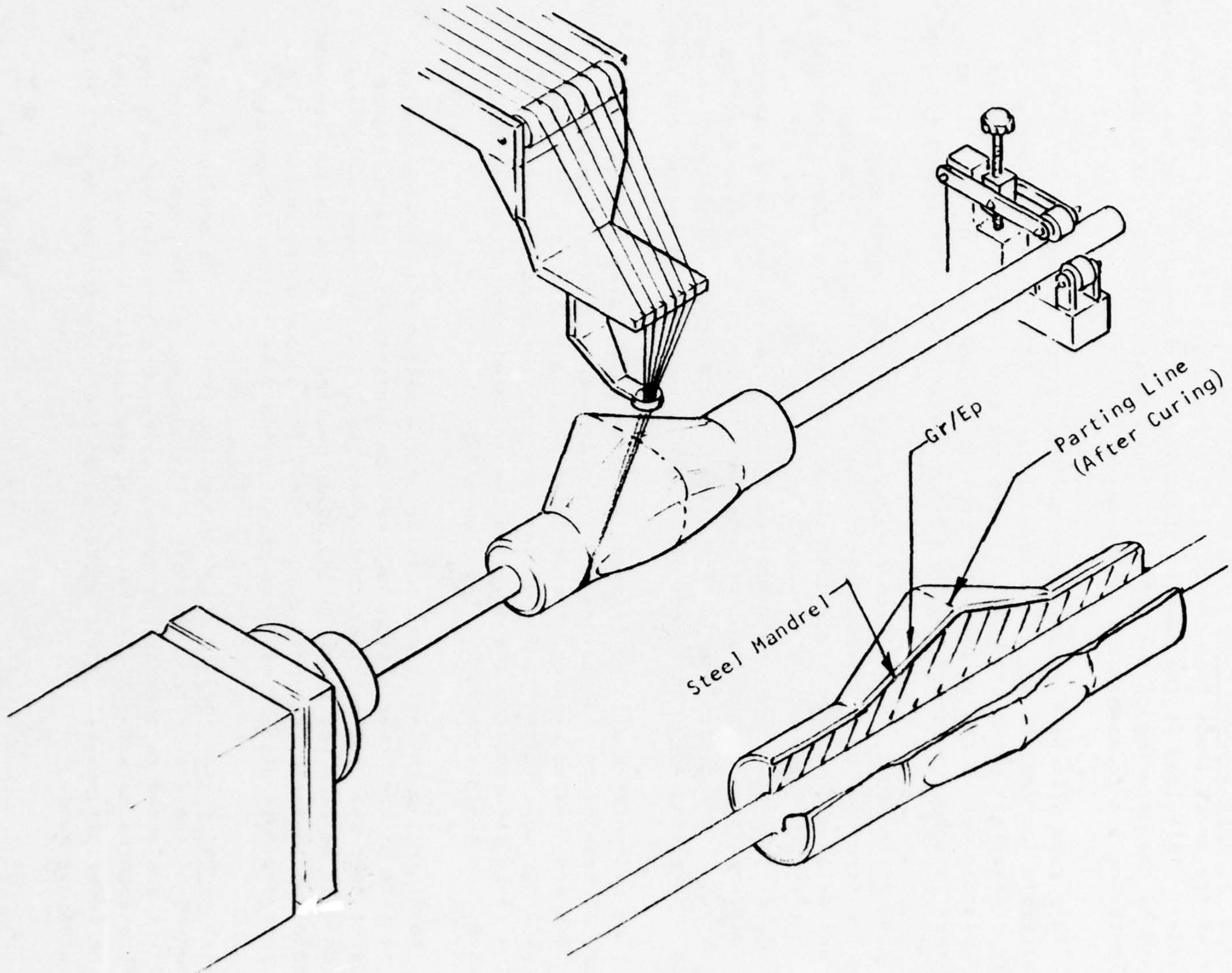


Figure 32. Trunnion Support - Filament Winding Tooling

holes will then be drilled in the trunnion support cone and the cylindrical bushings adhesive bonded in place.

4.3.1.3 Orifice Support Tube. The orifice support tube is a cylinder which carries the axial loads from the orifice to the upper fitting on the strut cylinder. This load is the landing shock load which results from the pressure caused by the metering of the hydraulic fluid between the orifice plate and the metering pin to absorb the impact energy.

This tube will be filament wound on a two piece mandrel which will disassemble for removal of the cured cylinder. Reinforcement bands of 90° (circumferential) plies are wound on each end to resist the "brooming" of the cylinder due to radial pressure from the conical shape of the fitting. The tube is adhesive bonded and then blind riveted to the metal end fittings.

4.3.1.4 Piston/Fork. The piston/fork is a structural member which fits into the strut cylinder and is subjected to pressure loads in the upper piston end and axial and bending loads over the entire length from the piston upper end to the fork lower end. The wheel and axle is mounted in the fitting at the end of the fork. The loads applied by the axle are resisted by the upper and lower bearings in the strut cylinder and the hydraulic pressure acting against the inner piston shell. The piston/fork assembly consists of three parts; the piston/fork, the inner piston shell and the axle support fitting.

The piston/fork will be filament wound on an inflated mandrel which is a body of revolution. Additional 90° reinforcement plies will be added to the fork end. After winding, the wet part will be placed in a mold and the wet windings post-formed to the offset fork configuration and cured. The part will be removed from the mold and the inflated mandrel collapsed and removed from the piston/fork. See figure 33.

Machining, both inside and outside on the piston end will be required. The outside of the lower piston body must be finished to close tolerance since it must seal against the strut lower bearing. The upper end of the piston must be machined to match the upper bearing. The inside surface must be machined to match the inner piston shell for a good adhesive bond joint. The fork end must also be machined to match the axle fitting for bonding.

4.3.1.5 Inner Piston Shell. The inner piston shell is the pressure vessel component of the piston/fork assembly. The dome end of the inner piston shell is subjected to the maximum hydraulic pressure generated between the orifice and the metering pin. These loads are resisted by the side walls of the inner piston shell and transferred to the piston/fork side wall through the adhesive bond.

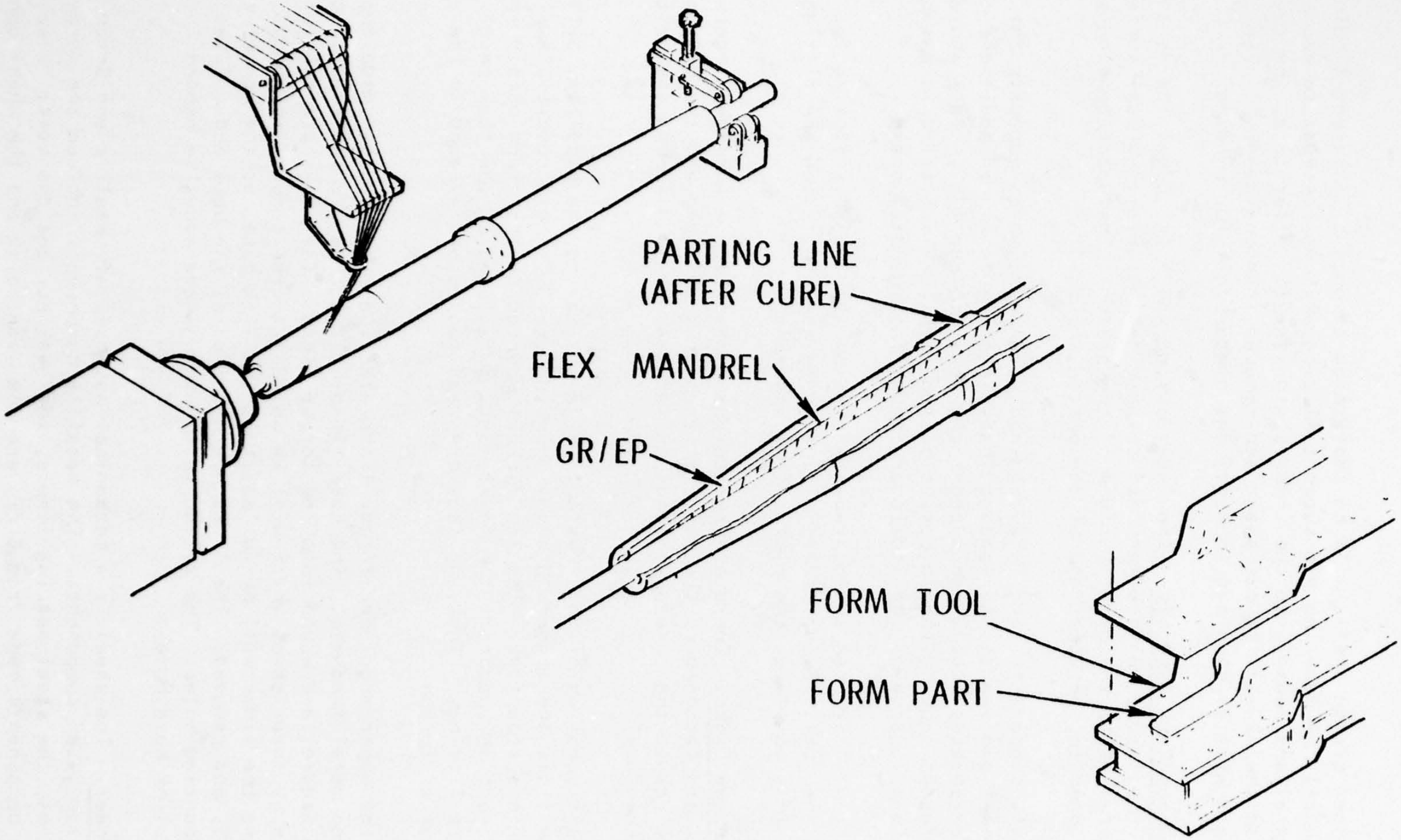


Figure 33. Piston/Fork Filament Winding and Forming Tooling

Two inner piston shells will be fabricated at once by filament winding on a metal mandrel. A metering pin support fitting will be fastened to each end of the mandrel and wound into the inner piston shell. After cure, the two inner piston shells will be cut apart and removed from the mandrel. The outer surface will be machined to match the piston/fork for bonding.

4.3.1.6 Piston/Fork Assembly. The inner piston shell is bonded inside the piston and the inside surface machined to provide a true cylindrical surface which is parallel to the outer surface of the piston. The upper bearing/snubber valve is pinned to the upper end of the piston.

The axle support fitting is a machined steel part which supports the axle and wheel and reacts the landing loads into the fork. In addition, this fitting incorporates lugs which support the lower torque link. This avoids having to fasten lugs to the composite piston/fork. This fitting is extended up to the fork to provide the stationary mount for the disk brake.

Tooling will be used to locate and hold the axle support fitting for bonding to the fork. Blind rivets will also be used to fasten the fitting to the fork. This completes the piston/fork assembly.

4.3.1.7 Torque Links. There are two torque links which are hinged together at the apex and fastened at the base, to the strut cylinder and the piston/fork. They resist the torsional loads on the gear while allowing the vertical motion of the fork.

The configuration of this system, while similar to the baseline, differs in that the links are longer to allow mounting that is more compatible with the composite piston/fork. The top link is mounted on the trunnion pin in the strut trunnion support. The lower link is fastened to the fork metal axle support fittings. Thus, no lugs are required to be fastened to the composite strut or fork.

Both the upper and lower torque links are filament wound and made two at a time on metal mandrels. The apex titanium fittings are fastened to each end of the mandrel and wound into the torque links. The links are reinforced at the base by interleaves which will be wound into the torque link body. After curing the links will be cut apart at the link base, at the center of the mandrel, and removed. The links are machined at the base and drilled for the base mounting holes. The cylindrical bushings are adhesive bonded into the torque link base holes.

4.3.1.8 Wheel. The wheel is a mechanical assembly of metallic and Gr/Ep composite laminated components. The metallic components include the forged aluminum rims, the steel bearing liners, the bearings and the steel false axle. The components made from Gr/Ep are the wheel disk and the wheel cone

which includes the hubs and the rim bolting rings. This wheel configuration, using a "cantilever" tire, provides room for a larger diameter and more efficient brake stack. This requires that the brake key support be simi-cantilevered from the wheel rim. Aluminum has been selected as the rim material. With ventilation holes between each brake key, it will dissipate heat better and provide a simpler installation for the brake keys.

The aluminum rim will also provide for a flat tire runout and while this is not a wheel specification requirement for single wheel assemblies, the MIL-A-8862 specification for multi-wheel assemblies, specifies flat tire loadings. Therefore, it appears appropriate that a more viable metal rim be used in this design.

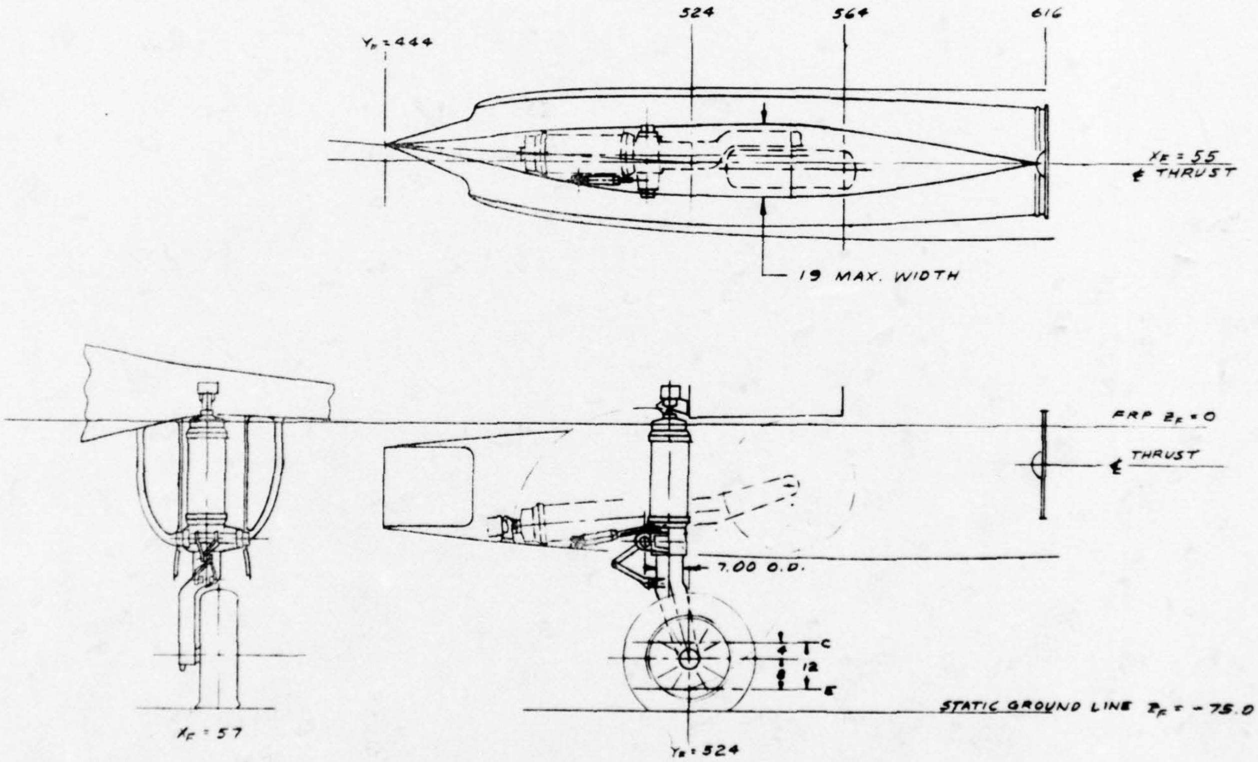
The wheel disk and the wheel cone components are Gr/Ep composite laminations cut into pie shaped segments and laid up with staggered butt joints on a metal mold. Interleaved reinforcements are added to both the hub and the rim bolting ring area. In addition, on the wheel cone the hub is reinforced with 90° circumferential overwraping. After curing, both parts are machined on the rim flange mating surfaces and on the hub inner surface for the bearing liners. The steel bearing liners are then adhesive bonded in place. The aluminum rims are made from 2014-T6 aluminum forgings. Both rims must be machined on; the bead seat, the mating and seal surfaces, the bolting flanges, and the brake key seat surfaces.

Assembly of the wheel and tire consists of mounting the tire on the inboard and outboard rims, positioning the inner wheel cone and the outer wheel disk to sandwich the rim flanges and installing the wheel assembly bolts. The bearings and the false axle are then installed. This completes the wheel assembly which may be accomplished in the shop to avoid installing bearings on the flight line.

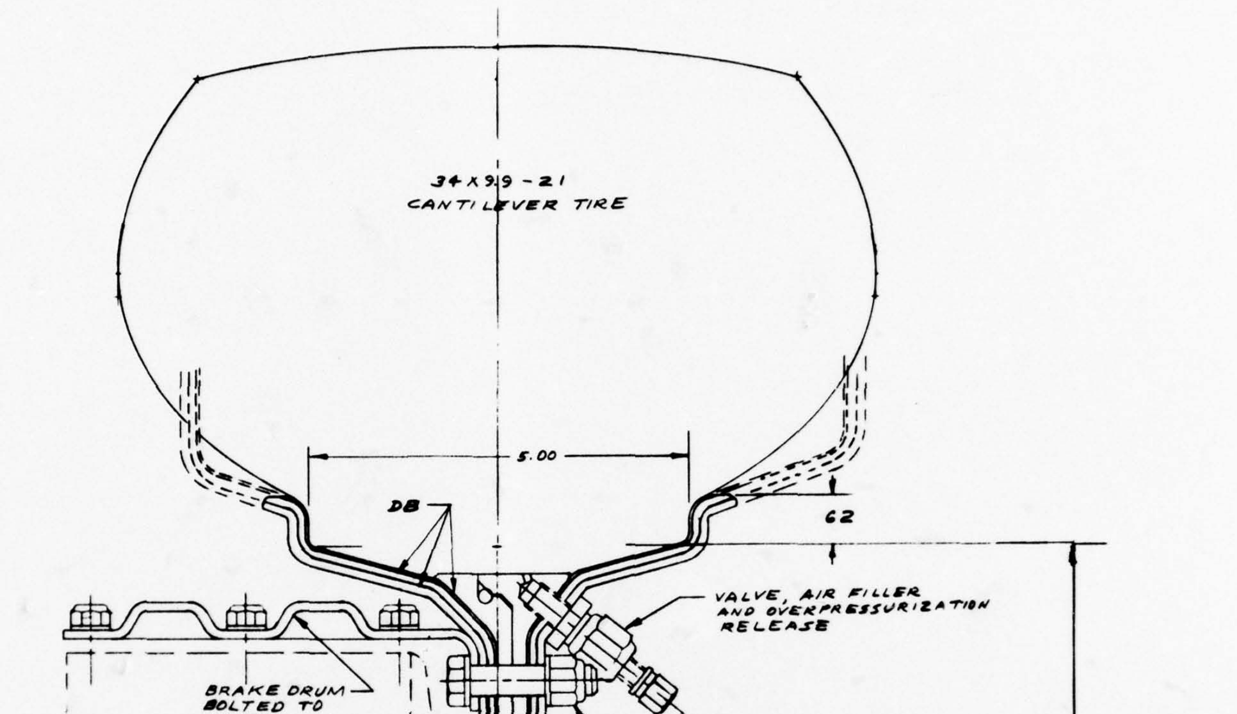
4.3.2 Advanced Metallic System Preliminary Design

A preliminary design, figure 34, of the conventional landing gear configuration, using SPF/DB titanium, has been made from conceptual designs studied previously in this section. This configuration uses the shock strut as the main structural member similar to the baseline design. Parts considered for SPF/DB titanium fabrication included the fork, the strut cylinder, the torque links and the wheel.

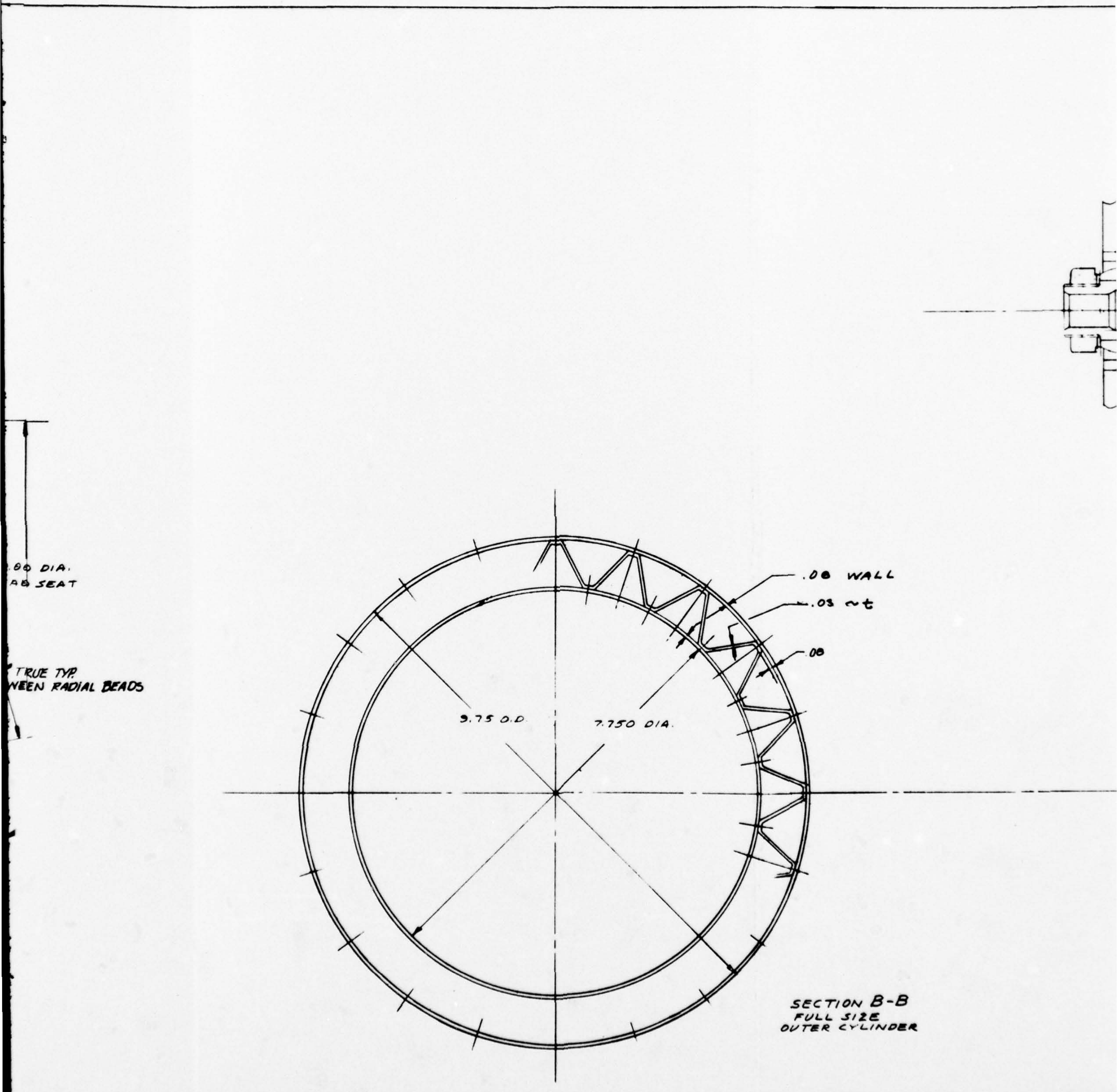
4.3.2.1 Fork. The single fork, which supports the axle and wheel, is a part of the piston/fork assembly. It is fabricated using the SPF/DB process and then welded to the lower end of the piston.



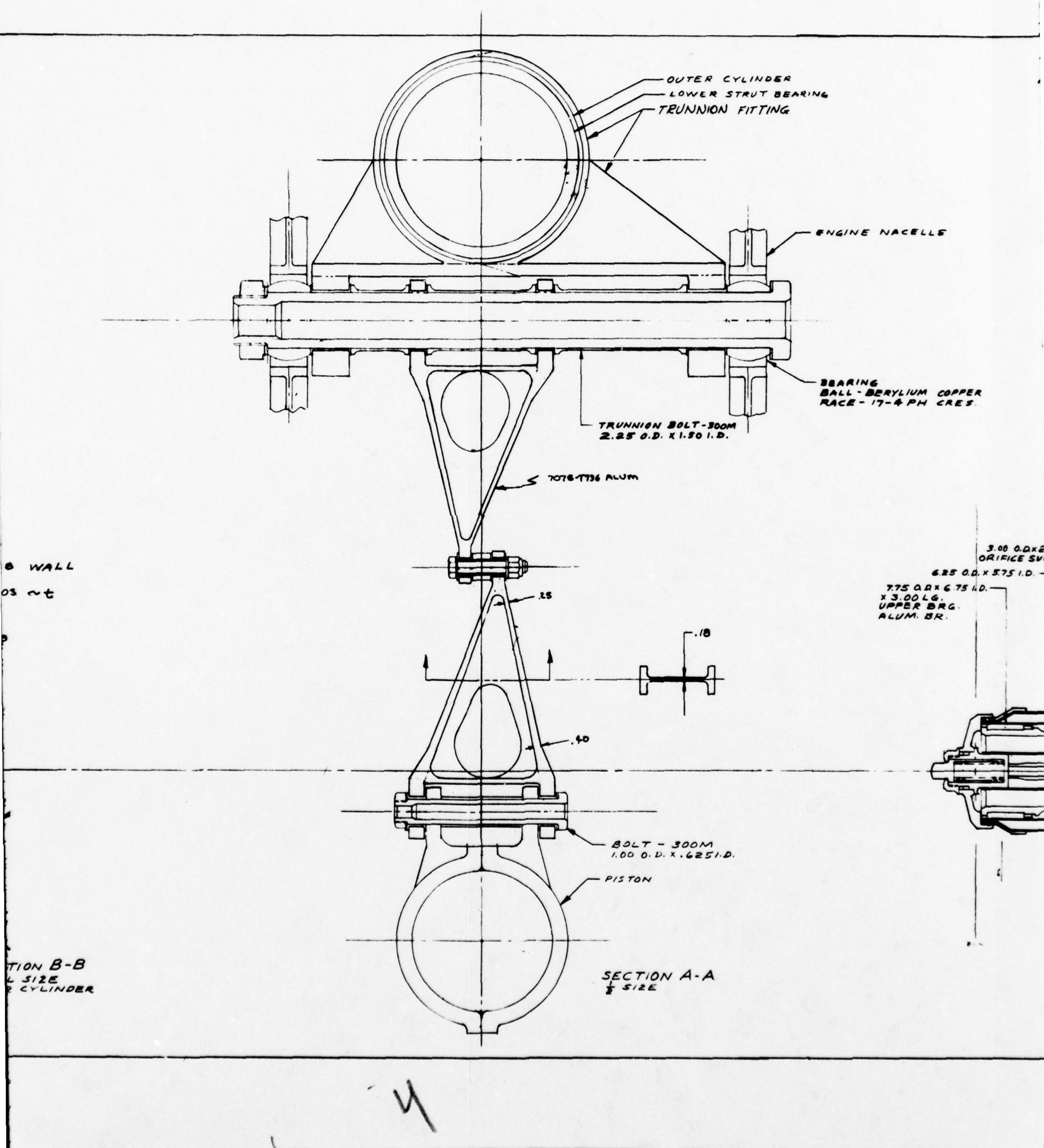
GENERAL CONFIGURATION
SCALE: $\frac{1}{20}$



DETAIL OF WHEEL
FULL SIZE

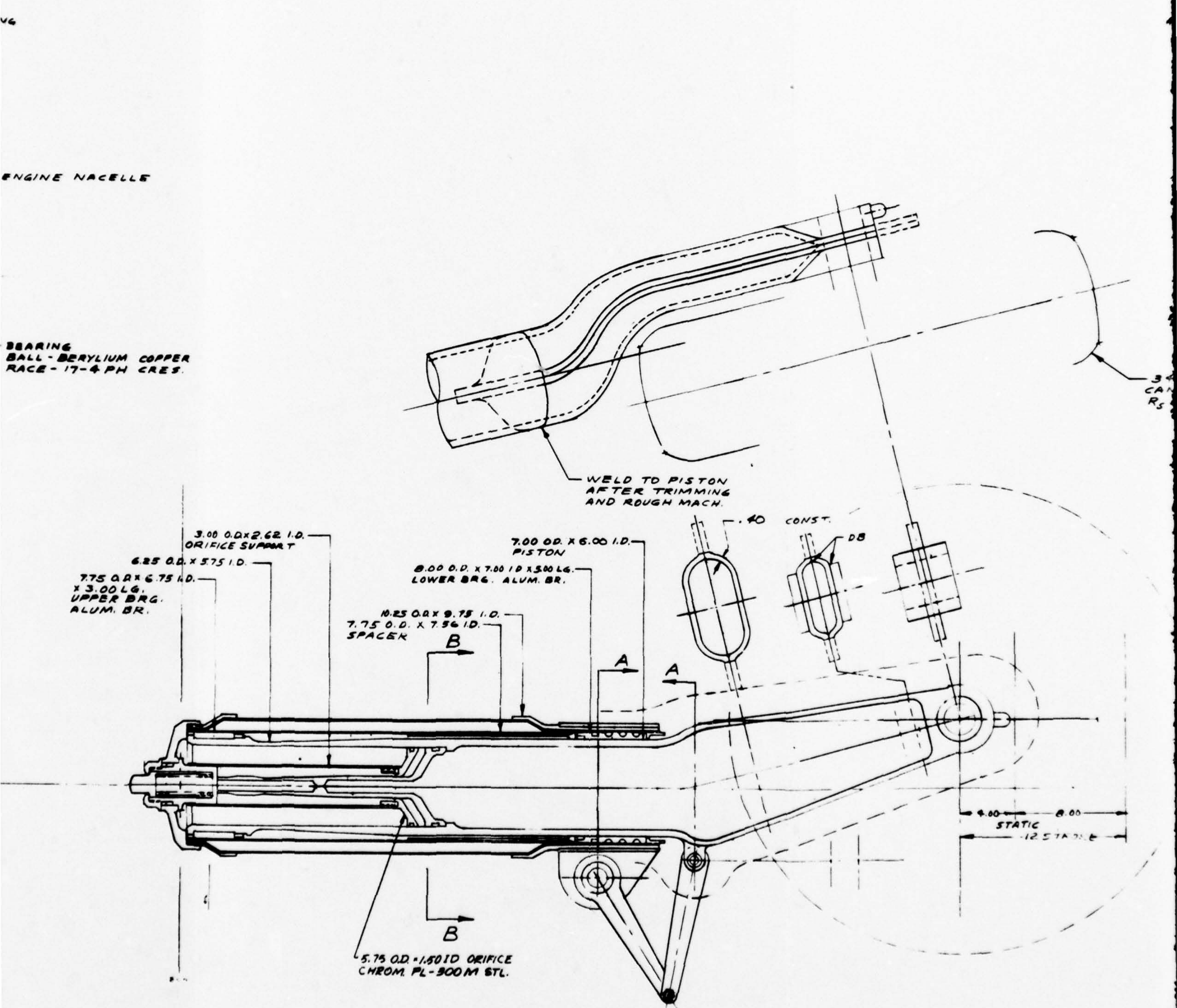


SECTION B-B
FULL SIZE
OUTER CYLINDER

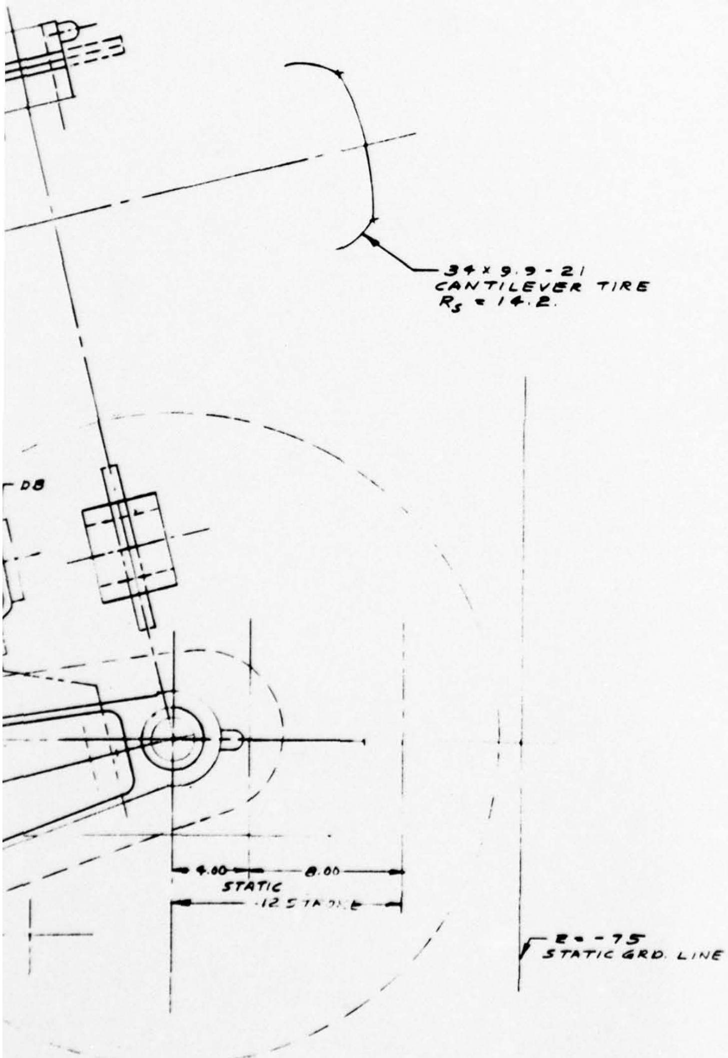


SECTION A-A
1/2 SIZE

4


ENGINE NACELLE
BEARING
BALL - BERYLIUM COPPER
RACE - 17-4 PH CRES.
WELD TO PISTON
AFTER TRIMMING
AND ROUGH MACH.
.40
CONST.
DB
3.00 O.D. x 2.62 I.D.
ORIFICE SUPPORT
6.25 O.D. x 5.75 I.D.
7.75 O.D. x 6.75 I.D.
x 3.00 LG.
UPPER BRG.
ALUM. BR.
7.00 OD. x 6.00 I.D.
PISTON
8.00 O.D. x 7.00 I.D x 3.00 LG.
LOWER BRG. ALUM. BR.
10.25 O.D. x 9.75 I.D.
7.75 O.D. x 7.56 I.D.
SPACER
B
A
A
B
4.00
8.00
STATIC
5.75 O.D. x 1.50 ID ORIFICE
CHROM. PL - 300M STL.

5



MATERIALS
ALL PARTS TITANIUM 6AL-4V
EXCEPT AS NOTED.

Figure 34

REV. 9-29-77

SCALE: 1/4 & NOTED	DR. H. J. HOFFMAN DATE 9-10-77 MODEL D619-3A	Rockwell International Corporation Los Angeles Aircraft Division INTERNATIONAL AIRPORT LOS ANGELES, CALIFORNIA	ADVANCED DESIGN
STUDY - PHASE II ATS MAIN LANDING GEAR ADVANCED TITANIUM			D615-1-413

6

The fork will consist of two side plates, two axle housing fittings and two torque link lug fittings. The plates will be bent and placed into the die with the fittings located by die cavities, see figure 35. Die and parts are then heated and pressure introduced between the fork side plates to bulge them into the die cavity and against the fittings so that all parts become diffusion bonded. After removal from the die, the part is then machined to final shape and welded to the piston.

4.3.2.2 Strut Cylinder. The strut cylinder is a pressure vessel and, in additon, has both axial and bending loads acting on it. The cylinder has been designed as a truss core sandwich structure to provide a more efficient section for axial and bending loads.

It will be fabricated using the SPF/DB process to form the sandwich structure and to join it to the trunnion lugs fitting and the cylinder end reinforcements. The inner, outer, and core sheets of the truss core are trimmed to size and coated with "stop-off" compound to control what areas will be diffusion bonded. These sheets are then placed on the cylindrical mandrel with the cylinder end reinforcements. The trunnion fitting is located in the lower die cavity and the mandrel, with all the other parts in place, is positioned in the lower die and the upper die secured in place.

The die and parts are brought up to temperature and pressure is introduced on the outside of the sheets on the mandrel to bond all parts together per the "stop-off" pattern. After bonding is completed, the pressure is diverted to the area between the inner and outer sandwich sheets which will cause the outer sheet to stretch up into the larger cylindrical cavity of the die, and to pull the center core sheet into the truss core configuration. After removal from the die the cylinder and the trunnion fitting are machined to final dimensions. See figure 36.

4.3.2.3 Torque Links. The torque links were designed as SPF/DB titanium parts, but preliminary evaluation revealed that these parts were not cost effective against aluminum parts similar to the baseline torque links.

4.3.2.4 Wheel. The wheel consists of two halves which are assembled with the tire and held together by bolts just under the rim. Each wheel half consists of the wheel disk, half of the wheel hub, the sealing ring and half of the rim. Both wheel halves will be made from titanium using the SPF/DB fabrication process concurrently to form the wheel disk and diffusion bond it to both the hub and the sealing ring.

The wheel disk consists of three sheets, an inner and outer disk and a ring which is the rim reinforcement. These parts are placed on the lower

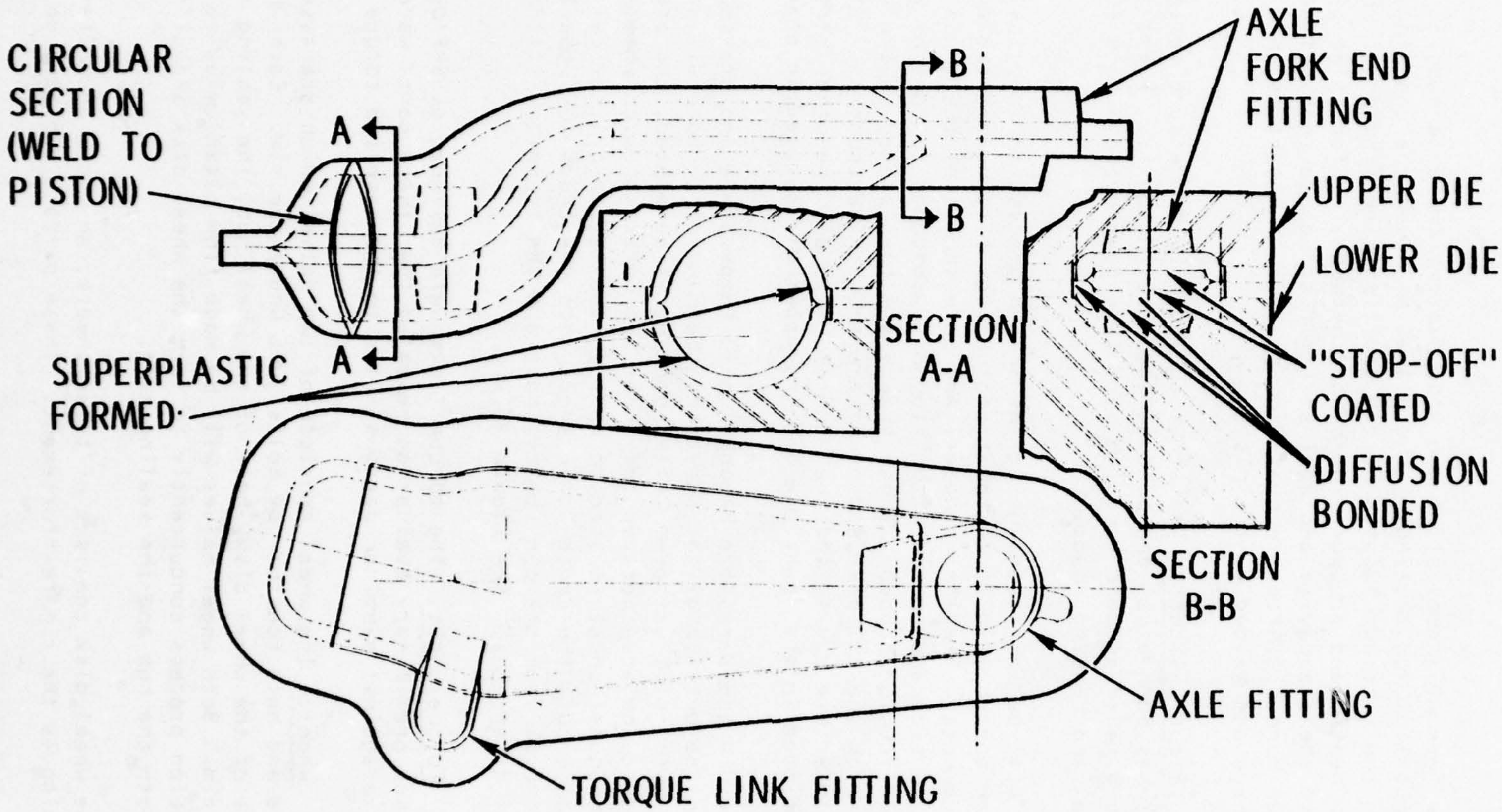


Figure 35. Fork - SPF/DB Tooling

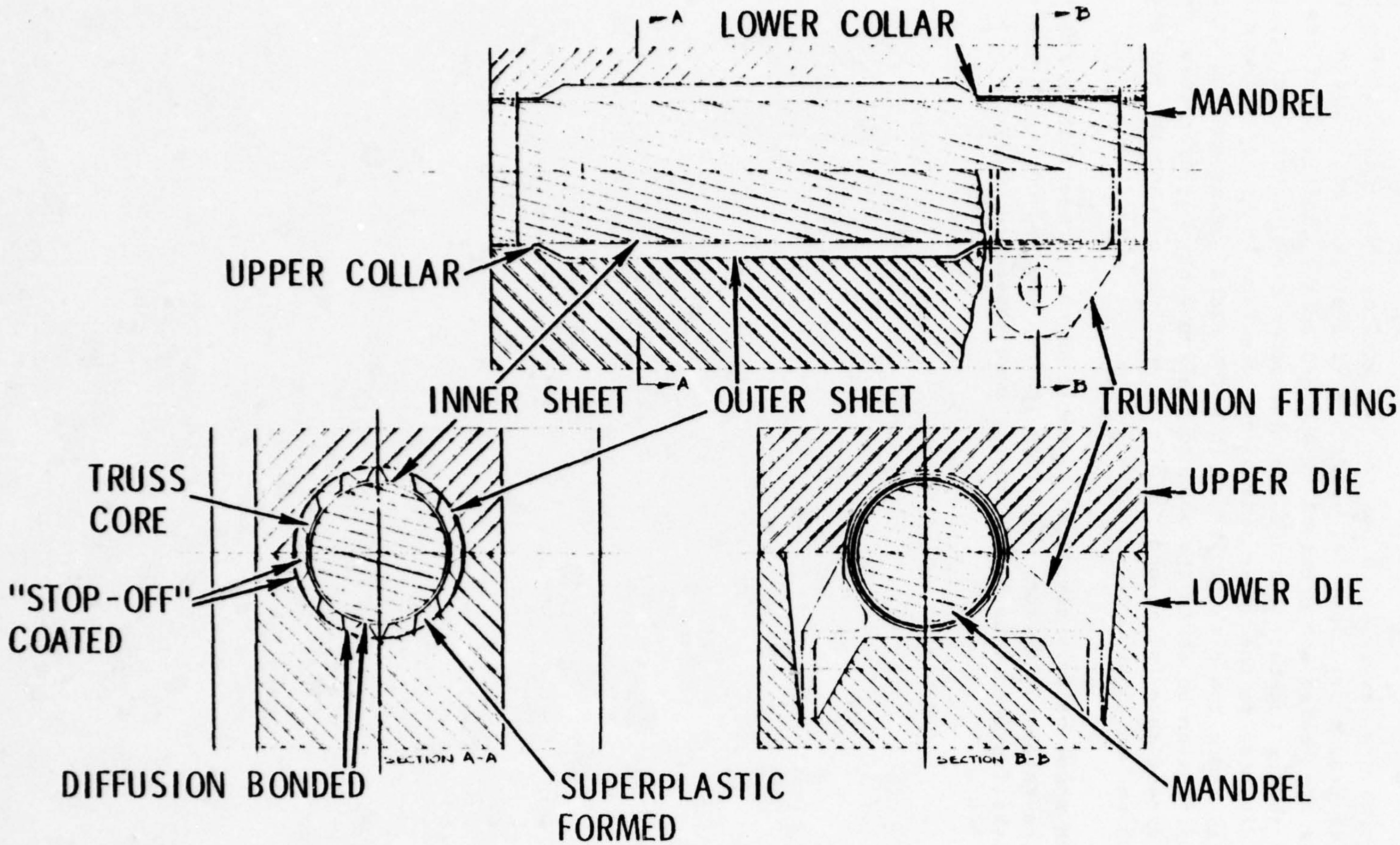


Figure 36. Strut Cylinder - SPF/DB Tooling

die over the die cavity which has the hub and the wheel sealing ring positioned in it, see figure 37. The flat upper die is then secured in place. The die and parts are heated and pressure is applied to the under side of the disks to bond the sheets together against the flat upper die. After bonding, the pressure is diverted to the upper side of the disk and it is forced down into the die cavity where the disk is formed into the radial beads configuration of the die and diffusion bonds to the hub and sealing ring. After removal from the die the excess material beyond the rim is machined off and the hub and sealing ring machined to final dimensions.

Each wheel half is completed by positioning the bearings in the hub and adding the retaining device. The tire is then mounted on the rims and the wheel disks fastened together using the wheel assembly bolts.

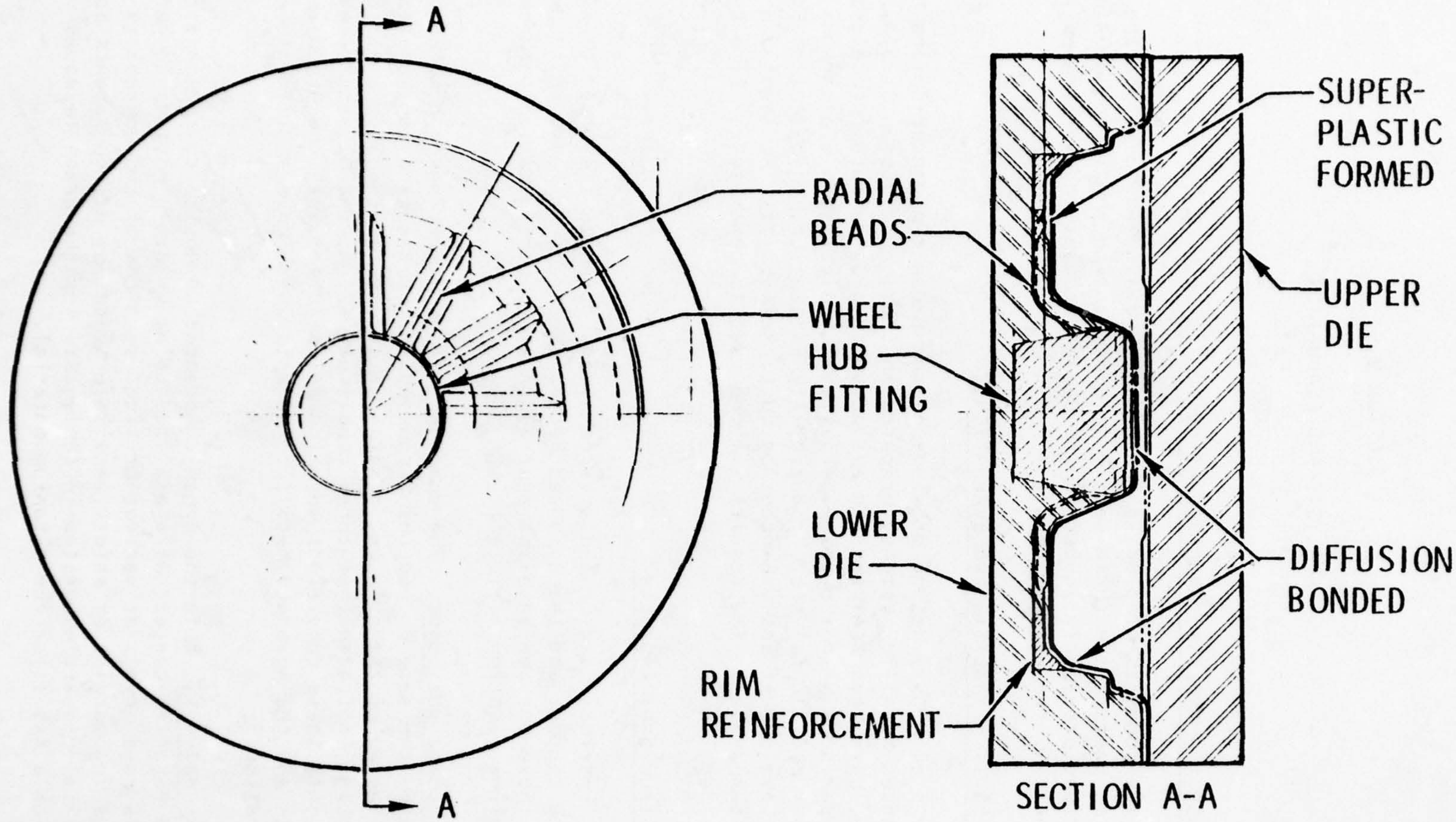


Figure 37. Wheel - SPF/DB Tooling

SECTION V

ANALYSIS AND EVALUATION

5.1 PHASE I - ANALYSIS AND EVALUATION

Design concepts studied in Phase 1 were evaluated to select the parts considered best in the three sections; Substitution, Modified and Redesigned, as described previously in Section IV Design Studies, and presented in detail in Appendix A, the Phase I report.

5.2 PHASE II - ANALYSIS AND EVALUATION

The preliminary design drawings of the Organic Advanced Composite and the Advanced Metallic systems, prepared in Section IV Design Studies for Phase II, have been analyzed and evaluated to provide data for weight and cost comparisons with the Baseline System. Analysis and evaluations made were: Structural Analysis, Producibility Evaluation, Installation Evaluation, Weight, Development Cost, Production Cost, Reliability, Accident and Maintenance Cost Analyses. The results will be used to generate the Life Cycle Costs in Section VI.

5.2.1 Structural Analysis

5.2.1.1 External Loads. The external loads for both the Organic Advanced Composite concept and the Advanced Metallic concept are assumed to be the same as those for the baseline gear (300M steel configuration), refer to the Baseline (Section III) text.

5.2.1.2 Component Loads. The component loads (reactions and moments) were obtained by the same procedures discussed in the Baseline section text. Since a review of the critical margins of safety for the 300M steel baseline gear concept indicated that three conditions (2, 4, and 8) determined the design, only these conditions were investigated for both the Organic Advanced Composite and the Advanced Metallic concepts which have similar geometric configurations.

5.2.1.3 Analysis. Both the Organic Advanced Composite concept and the Advanced Metallic concept were analyzed using standard methods to determine working stress levels at various critical sections of the components and combined loading margins of safety were determined for all components based on the material properties listed in table XXVI for the graphite/epoxy material, and in Table XXVII for the titanium material.

TABLE XXVI

ROOM TEMPERATURE MATERIAL PROPERTIES

1980 GRAPHITE/EPOXY

UNIDIRECTIONAL (t = 0.00525"/ply)

F_x^{tu} = 230 Ksi	E_x = 21.0 Msi
F_y^{tu} = 9 Ksi	E_y = 1.5 Msi
F_x^{cu} = 230 Ksi	G_{xy} = 0.7 Msi
F_y^{cu} = 25 Ksi	V_{yx} = 0.015
F_{xy}^{su} = 83 Ksi	V_{xy} = 0.210

$[03/\underline{+}45]_c$ LAMINATE

F_x^{tu} = 142 KSI	E_x = 13.8 Msi
F_y^{tu} = 27 Ksi	E_y = 3.2 Msi
F_x^{cu} = 153 Ksi	G_{xy} = 2.6 Msi
F_y^{cu} = 36.5 Ksi	V_{yx} = 0.145
F_{xy}^{su} = 55 KSI	V_{xy} = 0.635

F^{bru} = 50 Ksi (Minimum)

(1) X is 0° Direction, Y is 90° Direction

TABLE XXVII

MECHANICAL PROPERTIES AT ROOM TEMPERATURE -

SPF/DB TITANIUM

(Sheet in Thicknesses Below 0.180 Inch)			
Property	Value	Property	Value
F_{tu}, ksi	125	e, percent	10
F_{ty}, ksi	111	E, 10^6 psi	16.0
F_{cy}, ksi	117	E_c 10^6 psi	16.4
F_{su}, ksi	76	G, 10^6 psi	6.2
F_{bru}, ksi e/D=1.5	192	μ	0.33
e/D=2.0	246		
F_{bry}, ksi e/D=1.5	158	W, lb/in.^{3}	0.160
e/D=2.0	192		

A detailed discussion of the analysis will not be presented for the sake of brevity, however, a summary of critical or minimum margins of safety of both material systems is given in tables XXVIII and XXIX.

The designs for both material systems are considered to be structurally adequate in that no negative margins of safety were determined by this analysis.

5.2.2 Producibility

All three material systems and the concepts studied using them have been evaluated for producibility as a part of the Design Studies section.

The Metal Matrix Composite system was evaluated as a very high producibility risk in the Design Studies Evaluation conducted in Section IV. This was due mainly to the problems anticipated in fabrication of the cross ply orientations and the thickness of the metal matrix composite required for these multi-axially and highly loaded parts.

This Design Studies Evaluation rated both the Organic Advanced Composite and the Advanced Metallic systems as having only a moderate producibility risk, and they were selected for preliminary design studies. Landing gear components have not been fabricated on a production basis using either of these material systems and there is always moderate producibility risk in bringing a new system to production status.

The landing gear parts fabricated from the Organic Advanced Composite material Gr/Ep, use the filament winding technique on the shock strut cylinder, the trunnion support, the orifice support tube, the piston/fork, the piston inner shell, and the upper and lower torque links. The wheel disks are made by laying up segments of laminations on a metal mold.

Both of these fabrication methods have been used to make parts similar to the parts in figure 30. The tooling and fabrication procedures have been described in the Design Studies section, and do not pose any high risk producibility problems.

The advanced Metallic system uses superplastic forming and concurrent diffusion bonding (SPF/DB) of titanium as the fabrication method for the strut cylinder, the fork and the wheel, see figure 34. This process has been used at Rockwell to fabricate parts in many similar configurations, including truss core panels. The parts listed and the tooling and fabrication methods described in the Design Studies are not considered high producibility risks.

TABLE XXVIII

SUMMARY OF MINIMUM MARGINS OF SAFETY - GRAPHITE/EPOXY COMPOSITE GEAR

Gear Component	Critical Condition	Type of (1) Loading	Minimum Margin of Safety (M.S.)
Piston Tube			
At Upper Bearing	2	S	+ 4.38
4.5" Below Upper Bearing	2	S+B	+ 1.18
At Lower Bearing	4	S+B+HT	+ 0.13
Lower Piston Tube	4	S+B+A+TR	+ 0.878
Piston to Torque Link Lug	4	SO	+ 0.475
Upper Strut Pin	4	S+B	+ 0.297
Strut Tube			
At Upper Bearing	4	A+B+S+HT+M	+ 0.497
At Lower Bearing	4	A+B+S+HT+M	+ 0.830
Strut Tube Trunion Lug	8	SO	+ 0.042
Axle	4	S+B+TR	+ 0.033
Upper Torque Link			
Link	4	S+B	+ 0.119
End Lug	4	SO	+ 0.035
Lower Torque Link			
Link	4	S+B	+ 0.111
End Lug	4	SO	+ 0.079
Trunnion Pin	8	S+B	+ 0.70
Bearings			
Upper	2	BR	+ 0.079
Lower	2	BR	+ 0.003
Piston Inner Column	8	Col Stability	+ 0.314
Actuator Cylinder	-	HT+M	+ 0.06
Wheel	8	FS	+ 0.024
	8	BR (On Rim)	+ 0.075

(1) LOADING CODE: B = Bending Stress, A = Axial Stress, S = Shear Stress, HT = Hoop Stress, BR = Bearing Stress, SO = Shear-out Stress, TR = Torsional Stress, M = Meridional Stress, FS = Fastener Shear

TABLE XXIX

SUMMARY OF MINIMUM MARGINS OF SAFETY - SPF/DB TITANIUM GEAR

Gear Component	Critical Condition	Type of (1) Loading	Minimum Margin of Safety (M.S.)
Piston Tube			
At Upper Bearing	2	S	+ 5.23
4.5 Below Upper Bearing	2	S+B	+ 0.45
At Lower Bearing	8	S+B+HT	+ 2.58
Lower Piston Tube	4	S+B+A+TR	+ 0.938
Piston-to-Torque Link Lug	8	SO	+ 0.088
Upper Strut Pin	4	S+B	+ 0.184
Strut Tube			
At Upper Bearing	2	A+B+S+HT+M	+ 0.875
At Lower Bearing	8	A+B+S+HT+M	+ 0.870
Strut Tube Trunnion Lug	8	SO	+ 0.57
Axle	4	S+B+TR	+ 0.022
Upper Torque Link			
Link Web	8	S	+ 1.45
Link Cap	8	A	+ 0.075
End Lug	8	SO	+ 1.36
Lower Torque Link			
Link Web	8	S	+ 1.45
Link Cap	8	A	+ 0.075
End Lug	8	SD	+ 1.64
Trunnion Pin	8	S+B	+ 0.04
Bearings			
Upper	2	BR	+ 0.015
Lower	2	BR	+ 0.024
Piston Inner Column	8	A (Comp Yield)	+ 0.104
Actuator Cylinder	-	HT+M	+ 0.06

(1) LOADING CODE: B = Bending Stress, A = Axial Stress, S = Shear Stress, HT = Hoop Stress, BR = Bearing Stress, SO = Shear-out Stress, TR = Torsional Stress, M = Meridional Stress

5.2.3 Installation Evaluation

Installation of either the Organic Advanced Composite or the Advanced Metallic landing gear would require a wider wheel well. Since the wheel well is located in the splitter between the engine air intake ducts, the ducts and the nacelle have been revised to maintain adequate duct area.

The Advanced Metallic landing gear requires only a one-inch wider wheel well and therefore, only a minimal change in the ducts and nacelle. This increased size results in 8.8 pounds added to the duct and 9.7 pounds added to the nacelle.

The Organic Advanced Composite landing gear is much larger than the baseline and required that three-inches be added to the width of the duct splitter. This required a size and shape revision of both the ducts and the nacelle, as described in Section IV. A weight increase over the baseline of 34 pounds on the duct and 34.4 pounds on the nacelle resulted from changes. See figure 7.

5.2.4 Weight

Baseline landing gear weights were calculated from figure 6. These were presented in Section III Baseline, and are used in this section for comparison purposes. The weight of the components of both the Organic Advanced Composite and the Advanced Metallic landing gear designs, figures 31 and 34, have been calculated and are presented in table XXX. The advanced Metallics concept is lightest at a total weight of 1104 pounds and the Organic Advanced Composite concept heaviest at a total weight of 1208 pounds. The baseline concept weighed 1164 pounds.

5.2.5 Development Cost

The development costs of the Organic Advanced Composite design and the Advanced Metallic design have been estimated. These costs were developed similar to those for the baseline development costs which were described in Section III. Table XXXI shows these development costs and compares them to the baseline development costs. Two vendors provided development costs for the composite parts in the Organic Advanced Composite design and since they were different by a significant amount, they were presented separately as Vendor A and Vendor B.

The baseline design has the lowest development costs since it uses state-of-the-art materials. The Vendor B composite cost is next at $598,040 over baseline, while Vendor A is the highest cost at $988,040 over baseline, and Advanced Metallics is $680,860 over baseline development cost.

TABLE XXX

WEIGHT COMPARISON
MATERIAL SYSTEMS BY LANDING GEAR COMPONENT
(ATS MAIN LANDING GEAR) (POUNDS PER SIDE)

Nomenclature	Baseline (Steel) (lbs)	Organic Advanced Composites (Gr/Ep) (lbs)	Advanced Metallics (SPF/DB Ti.) (lbs.)
Tire	72.0	72.0	72.0
Wheel	66.0	109.0	67.8
Brake	94.5	94.5	94.5
Axle	9.1	22.3	10.5
Piston/Fork (Movable	143.4	98.6	113.0
Strut Cylinder	139.3	125.5	120.9
Torque Link - Upper	2.5	9.3	2.3
Torque Link - Lower	2.7	4.5	2.2
Actuators	7.4	7.4	7.4
Locks	19.6	19.6	19.6
Anti-Skid Detector	1.7	1.7	1.7
Oil	5.0	15.8	11.7
Misc. Pins & Fasteners	18.8	23.8	28.4
TOTAL lb/Side	582.0	604.0	552.0
TOTAL MAIN GEAR lb/ Air Vehicle	1164	1208	1104

TABLE XXXI

DEVELOPMENT COST COMPARISON

RDT&E COST

(In Thousands 1977 Dollars)

	Baseline	Advanced Metallic SPF/DB (Titanium)	Vendor A Composite (Graphite Epoxy)	Vendor B Composite (Graphite Epoxy)
Engineering				
Design	$ 393.04	$ 373.39	$ 491.30	$ 491.30
Test & Evaluation	275.13	261.37	343.91	343.91
Fatigue Drop Tests	107.00	235.00	250.00	250.00
Static Tests	82.00	176.00	190.00	133.00
Eng. Test Article	82.00	176.00	190.00	133.00
Test & Logistics Support	38.20	36.22	47.66	47.66
	$ 977.37	$1,257.98	$1,512.87	$1,398.87
Pre-Production (2 Shipsets)				
Fabrication	$ 378.00	$ 822.00	$ 880.00	604.00
Tooling				
Labor & Material	$ 150.00	$ 106.25	$ 100.54	$ 100.54
	$1,505.37	$2,186.23	$2,493.41	$2,103.41

5.2.6 Production Cost

The preliminary designs of the Organic Advanced Composite design and the Advanced Metallics design completed in Section IV Design Studies have been subjected to a detailed cost analysis. Hardware cost data for these designs were mainly "grass roots" or parametric estimates by manufacturing experts.

Cost estimates for the composite parts were obtained from two composite manufacturers and was used to supplement the costs developed from grass roots estimates. This resulted in two different cost estimates which are presented as Vendor A cost and Vendor B cost.

Costs of the Advanced Metallic design using SPF/DB titanium have also been based on "grass roots" estimates with the material costs based on the latest vendor quotes or catalog prices.

The tooling and fabrication concepts for both of these designs is described in Section IV Design Concepts. An 80% learning curve was used for both the composite and the advanced metallic designs. Assuming one release of 500 units for each of these designs, the true midpoint for either fabrication effort is unit 153.76. Adding the material cost and the prorated recurring costs of the tooling to the fabrication costs produces cost reduction curves of 85% for the composite design and 84% for the advanced metallic design, see figure 38.

Items not using composite materials or SPF/DB titanium were evaluated on current costs or estimates based on corporate standards and projected for production quantities. Thirty-five percent (by weight) of the parts used in either of these designs are identical to the baseline parts and another five percent are similar except they may be slightly lighter or heavier.

Costs developed for landing gear components which have been studied using different materials are shown in table XXXII. The strut cylinder, made from either Advanced Metallics, SPF/DB titanium or Organic Advanced Composites, by Vendor B, is the only part that offers a cost savings over the baseline ($3590 for Vendor B composite part and $1200 for the advanced metallic part).

Complete landing gear production costs are shown in table XXXIII where they are listed for comparison with the costs for the baseline design. The Vendor B average production shipset cost is lowest with the baseline cost next at $9353 more and the advanced metallic concept $20,738 more and the Vendor A organic advanced composite $31,328 more than Vendor B costs.

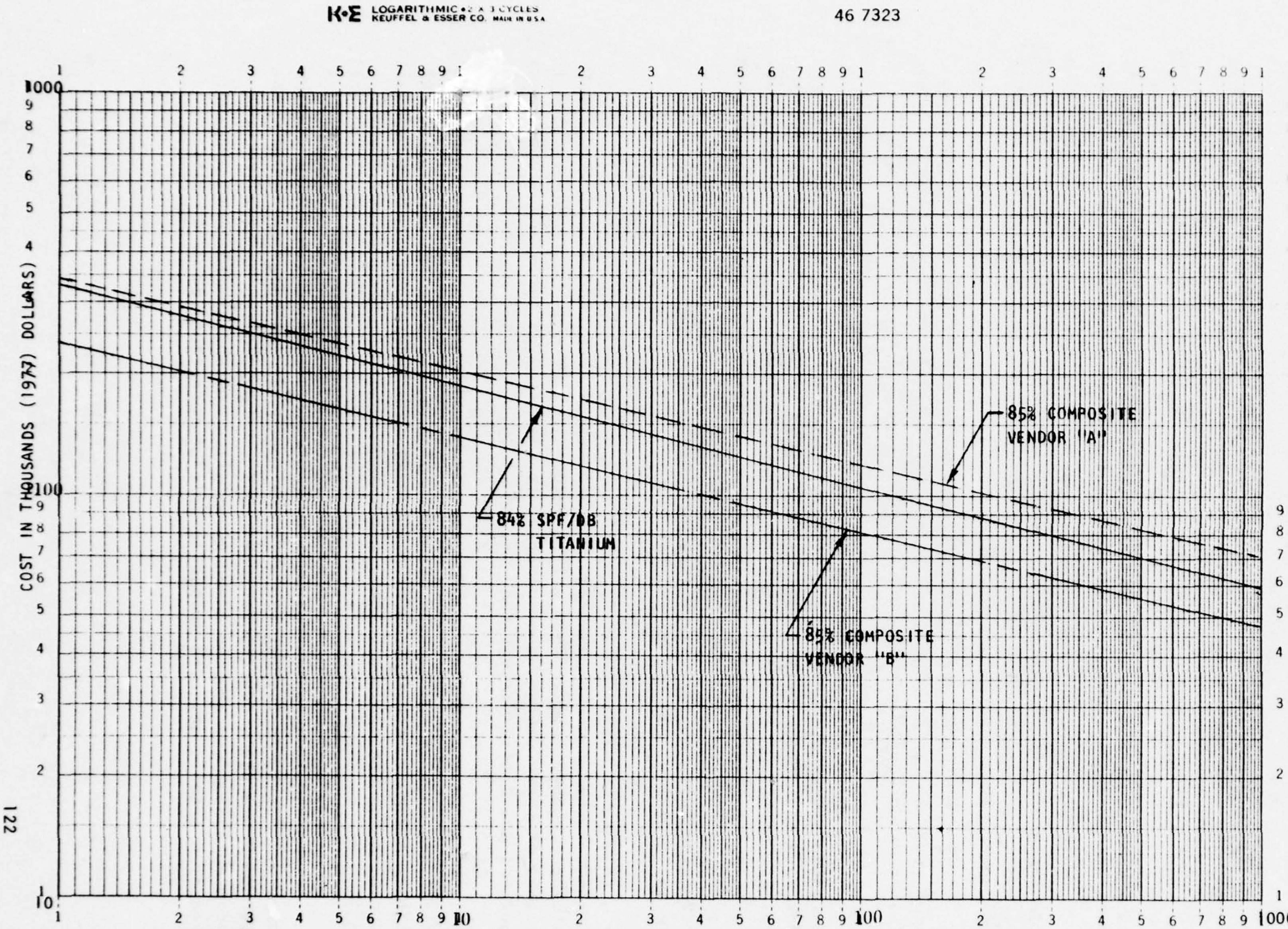


Figure 38. Landing Gear Study-Production Cost Per Shipset (Unit Cost)

TABLE XXXII

LANDING GEAR UNIT COSTS COMPARISON BY COMPONENT

(Thousands of 1977 Dollars/Side)

Component	Baseline	Vendor A COST Organic Advanced Composites	Vendor B COST Organic Advanced Composites	Advanced Metallics
Strut Cylinder	14.3	15.30	10.71	13.1
Piston/Fork	11.1	22.00	17.42	16.4
Torque Link-Upper	.4	.59	1.83	.4
Torque Link-Lower	.4	.42	1.59	.4
Wheel Assembly	1.4	6.40	4.95	3.5
Total	27.6	44.71	36.50	33.8

TABLE XXXIII

PRODUCTION COST COMPARISON

(1977 Dollars)
500 Shipsets

	Baseline	Vendor A Organic Advanced Composites	Vendor B Organic Advanced Composites	Advanced Metallics
Nonrecurring Costs				
Tooling Hours	(19,418)	(13,500)	(13,500)	(14,276)
Tooling Dollars	$ 544,400	$ 370,845	$ 370,845	$ 392,162
Tooling Material	$ 45,978	$ 31,320	$ 31,320	$ 33,120
Total	$ 590,378	$ 402,165	$ 402,165	$ 425,282
Recurring Costs				
Fabrication Hours	(755,729)	(503,679)	(503,679)	(1,019,156)
Fabrication Dollars	$22,626,526	$15,085,200	$15,085,200	$30,513,535
Production Material	$13,816,634	*$33,122,800	*$17,057,100	$11,952.950
Tooling Hours	(19,699)	(13,419)	(13,419)	(14,190)
Tooling Dollars	$ 514,134	$ 368,620	$ 368,620	$ 389,799
Tooling Material	$ 45,702	$ 31,132	$ 31,132	$ 34,234
Tires; brakes; antiskid detector	$ 3,519,000	$ 3,519,000	$ 3,519,000	$ 3,519,000
TOTAL RECURRING COST	$40,548,996	$52,126,752	$36,061,052	$46,409,518
CUMULATIVE SHIPSET COST - AVE. AT 500 SHIPSETS	$ 82,279	$ 104,254	$ 72,926	$ 93,664

* Purchased Composite Parts included as Production Material

COSTS SHOWN PROVIDE A RELATIVE COMPARISON OF CONCEPTS FOR DESIGN EVALUATION. THESE COSTS DO NOT INCLUDE ALL ELEMENTS REQUIRED FOR PRICING. ESTIMATES FOR FACILITIES, EQUIPMENT, RESEARCH, DEVELOPMENT, TEST, AND ENGINEERING ARE NOT INCLUDED.

5.2.7 Reliability

The reliability of the baseline landing gear hardware was presented in Section III and a reliability analysis has been completed for the Advanced Organic Composite and the Advanced Metallic designs. The reliability factors that were determined for each design, for use in computing life cycle costs, were the corrective "Maintenance Demand Rate" (MDR) and the condemnation rates which are presented in table XXXIV.

For those components that were the same or made from similar metal, the same reliability rates that were developed for the baseline in Section III were used for the alternate designs. These components constituted the majority of the corrective MDR's (97%) and condemnation rates (98.5% to 99.4%). The components include tire, brake stack assembly, brake actuator assembly, strut actuator, downlock assembly, uplock assembly, anti-skid detector and the axle. The total MDR for these components is 23,751 and the condemnation rate is 2800.5 per 10^6 flight hours. They are shown in table XXXIV as subtotals.

For those components that were different in the alternate designs, the baseline MDR's and condemnation rates were changed to reflect the reduction or elimination of failures due to corrosion. Review of landing gear data from Hill Air Force Base indicates that stress corrosion is a major factor in landing gear repair and replacement. AFM 66-1 data were reviewed to determine the impact of corrosion on the MDR and condemnation rates of landing gear components. Corrosion associated modes of failure averaged 11% for landing gear component MDR's and 46% to 79% for condmenation rates for landing gear components and wheel assemblies, respectively.

Components made completely of a composite were estimated to be corrosion free and the rates reduced accordingly. Components made of both metal and composites were reviewed on an individual basis. In the case of the wheel assembly, which was designed with some aluminum and some composite elements, the MDR was reduced by 2.6%. Where there is movement between metallic and composite elements, i.e., the piston, it was assumed there would be a 6% increase in the MDR.

Since titanium is corrosion resistant, but not corrosion free, the MDR's were predicted to be 7% less than the baseline. The resultant change in the rates for those baseline components that were redesigned to use composite and titanium materials ranged from 7% for the MDR to 60% for the condemnation rate (table XXXIV). This resulted in a significant change in sparing cost and a minor change in personnel costs.

TABLE XXXIV
MAIN LANDING GEAR ALTERNATE CONCEPT
RELIABILITY COMPARISON

Work Unit Code	Component Name	Qty Per A/C	Corrective MDR X10^6 Hours/Aircraft			Condemnation Rate X10^6 Hours/Aircraft		
			Baseline	Composite	Advanced Metallic	Baseline	Organic Composite	Advanced Metallic
13BAA9A	MLG Cylinder	2	270.0	241.9	251.3	27.0	19.6	13.1
13CDA9*	Wheel Assembly	2	250.0	243.5	232.7	12.5	2.7	2.6
13EAQ1	Torque Link-Upper	2	22.0	19.7	20.5	1.1	0.5	0.5
13EAQ2	Torque Link-Lower	2	22.0	19.7	20.5	1.1	0.5	0.5
13BAA9B	MLG Piston	2	14.0	14.8	13.0	0.1	1.5	0.1
	Subtotal - Rates (A)		578.0	539.6	538.0	41.8	24.8	16.8
	Percent Reduction in Rate		0	6.6	6.9	0	40	60
	Subtotal - Rates (B) (Components* with same rates for each material system)		23,751	23,751	23,751	2,800.5	2,800.5	2,800.5
	GRAND TOTAL RATES (Σ Subtotals A+B)		24,329	24,290.6	24,289	2,842.3	2,825.3	2,817.3

* Components include Tire, Brake Stack Assembly, Brake Actuator Assembly, Strut Actuator, Downlock Assembly, Uplock Assembly, Anti-Skid Detector and Axle.

5.2.8 Maintenance

The Organic Advanced Composite and the Advanced Metallics preliminary designs, figures 30 and 34, completed in Section IV have been analyzed to provide maintenance cost comparisons to the baseline for a 10 year support time span. Since the configurations of both of these designs are similar to the baseline configuration, the identifiable maintenance tasks and the maintenance analysis methodology is the same as that used in the baseline maintenance analysis described in Section III. The Baseline MDR's are shown in table XV and a comparison of MDR for all three designs is presented in table XXXIV. The MDR for tires shown in table XV is based on actual tire failure plus wear, which requires that tires must be replaced or retreaded every 100 flight hours (FH). See Appendix E for details. Off-Aircraft task time is 20 minutes on Baseline and 25 minutes on Organic Composite or Advance Metallic due to number of parts and fasteners.

Subsystem scheduled inspections will be reduced for the Advanced Material systems due to the improved corrosion resistance of the materials. The inspections MDR's are: Baseline = 20,000; Organic Composite = 5,000 and the Advanced Metallic = 10,000 per 10^6 flight hours. The Maintenance Actions for Preflight and Postflight servicing and lubrication are the same for all three designs.

The support costs were estimated as an increase or decrease from the baseline support costs presented in table XX, Section III.

The change (Δ) in support cost is given by the following equation:

Δ Support Cost = Δ Spares Cost + Δ OSE Cost + Δ Personnel Cost.

The change in these costs is given by the equations below:

Δ Initial Spares Cost = Initial Spares Cost (new design) - Initial Spares Cost (Baseline)

Δ Recurring Spares Cost = Recurring Spares Cost (new design) - Recurring Spares Cost (Baseline)

Δ OSE Cost was zero since there is virtually no difference in the three configurations. Support equipment is, for the most part, a function of the configuration of the parts and the position in the aircraft and not the material.

Δ Personnel Cost = Δ Maintenance Demand Rate (MDR)
x Quantity per Aircraft
x Total Fleet Flying Hours
x Cost/Productive Manhours
x Maintenance Task Time

The increase or decrease in support cost for the Organic Advanced Composite or the Advanced Metallic designs from the Baseline design is given for each component of the landing gear in table XXXV. The Advanced Metallic system support costs are \$382,400 lower than the \$9,827,600 Baseline support costs. The differences in cost of Organic Advanced Composite spares between Vendor A and Vendor B result in support costs which are \$178,300 higher than baseline for Vendor A and \$213,100 lower than baseline for Vendor B.

5.2.9 Evaluation

Results from the foregoing analysis and evaluations have been studied and are compared and discussed below.

5.2.9.1 Total Landing Gear System Comparisons. All three material systems can be designed to meet the structural requirements of the landing gear and there is only a moderate producibility risk in using either the Organic Advanced Composite design or the Advanced Metallic design.

Installation of the Organic Advanced Composite landing gear requires the greatest change in the nacelle which added 68.4 pounds to the baseline air vehicle weight. The nacelle changes for the Advanced Metallic design added only 18.5 pounds over the baseline weight. This is because the ATS aircraft is "volume limited" in the wheel well area. The nacelle must be increased in size and weight, at increased cost to provide room for a larger, though lighter, landing gear.

The total weights given in table XXX shows that the Advanced Metallic design is lighter than the baseline and the Organic Advanced Composite design is heavier than the baseline.

Development costs are higher for the advanced material systems. The Vendor B, Organic Advanced Composite development costs are lower than the Advanced Metallic, while the Vendor A development costs are higher.

Production unit (shipset) costs are lowest for Vendor B, Organic Advanced Composite system, while both the Vendor A, Organic Advanced Composite and the Advanced Metallic system costs are higher than the baseline.

The reliability of both advanced material systems is better than the baseline. As measured by MDR, they are about 7% better than the baseline However, as measured by Condemnation Rate, the Organic Advanced Composite system is 40% better and the Advanced Metallic system is 60% better than the baseline system.

Maintenance costs are lower than the baseline system for both the Advanced Metallic system and the Organic Advanced Composite system from Vendor B; however, using Vendor A spares costs, the maintenance costs would be higher.

TABLE XXXV

SUPPORT COST COMPARISON

10 Year Life Span - Costs in Thousands of 1977 Dollars

		BASELINE TOTAL COSTS (STEEL)				Δ COST - ORGANIC ADVANCED COMPOSITES						Δ COST ADVANCED METALLICS			
			PERSONNEL					PERSONNEL					PERSONNEL		
Part Nomenclature	WUC Number	Spares Initial & Recurring	On Aircraft	Off Aircraft	Total Cost	Vendor A Spares Initial & Recurring	Vendor B Spares Initial & Recurring	On Aircraft	Off Aircraft	Vendor A Δ Total Cost	Vendor B Δ Total Cost	Spares Initial & Recurring	On Aircraft	Off Aircraft	Δ Total Cost
Tire	13CDA9C	4412.4	422.4	192.0	5026.8				+32.0	+ 32.0	+ 32.0			+ 32.0	+ 32.0
Brake Stack Assy.	13EAC	235.2	44.9	19.8	299.9										
Brake Actuator Assy.	13EBE	156.9	59.9	41.9	258.7										
Strut-Hydraulic Actuator	13CBL	32.3	13.2	8.6	54.1	- 0.3	- 0.3	- 0.1	- 0.1	- 0.5	- 0.5	+ 1.2	- 0.1	- 0.1	± 1.0
Main Landing Gear Cylinder	13BAA9A	864.6	22.3	6.7	893.6	+ 222.1	-103.4	- 2.5	- .7	+ 218.9	- 106.6	-348.9	- 3.4	- 0.4	-352.7
Wheel Assy.	13CDA9*	56.0	13.4	2.8	72.2	+ 98.6	+ 62.9	- 0.3	- 0.1	+ 98.2	+ 62.5	+ 30.0	- 0.9	- 0.2	+ 28.9
Up/Down Lock Assy.	13BAC1,2	45.2	22.3	6.3	73.8							- 1.1	- 1.1	- 0.2	- 2.4
Torque Link Upper	13BAQ1	8.9	1.0	0.4	10.3	+ 3.4	+ 29.2	- 0.1	- 0.1	+ 3.2	+ 29.0	- 0.4	- 0.1	- 0.1	- 0.6
Torque Link Lower	13BAQ2	8.9	1.0	0.4	10.3	0	+ 19.5	- 0.1	- 0.1	- 0.2	+ 19.3	- 0.4	- 0.1	- 0.1	- 0.6
Main Landing Gear Piston	13BAA9B	224.6	1.9	0.2	226.7	+ 114.9	+ 39.4	+ 0.1	0	+ 115.0	+ 39.5	+105.3	- 0.2	0	+105.1
Anti-Skid Detector	13GCB	16.3	0.4	0.0	16.7										
Axle	13BAA9C	89.7	1.6	0.2	91.5	- 0.3	- 0.3			- 0.3	- 0.3	- 0.3	0	0	- 0.3
Preventive Maintenace		---	2793.2	---	2793.2			-288.0		- 288.0	- 288.0	--	-192.8	---	-192.8
BASELINE TOTAL		6150.8	3676.8		9827.6										
Δ TOTAL						+ 438.4	+ 47.0	-260		+ 178.3	- 213.1	-214.6	-167.8		-382.4

A summary of the above evaluations is presented in Table VI. An examination of this chart does not reveal which material system is best since the Advanced Metallic system is the lightest weight and has the lowest maintenance costs, but the Vendor B, Organic Advanced Composite system, has the lowest production costs and the Baseline system has the lowest development costs. A life cycle cost analysis must be made before the most cost effective material system can be determined for the ATS aircraft.

5.2.9.2 Selected Best Components Comparisons. An evaluation has been made using selected components to obtain a more general picture of the effects of using advanced materials for landing gears when the aircraft is not "volume limited," that is, the larger stowage requirements for advanced materials would not increase the size of the aircraft.

An examination of the weights of individual components in table XXX presents a different picture of the merits of the material systems than is shown by the weight totals. The Gr/Ep wheel with the aluminum rim used in the Organic Advanced Composite design is very heavy and has a large effect on the weight of the whole system, while other parts yield weight savings.

Other than the wheel, the strut cylinder, the piston/fork, and the two torque links are the main parts studied in the advanced material systems. An examination of these items, plus the hydraulic oil necessary for different sized cylinders, reveals that these Organic Advanced Composite parts save 39.2 pounds and Advanced Metallic parts save 42.8 pounds when compared with the baseline weight, see table XXXVI.

TABLE XXXVI
COMPONENT PART WEIGHT COMPARISON
(Weight in Pounds/Side)

Part Nomenclature	Weight Baseline	Δ Weight	
		Organic Advanced Composites	Advanced Metallics
Strut Cylinder	139.3	- 13.8	- 18.4
Hydrualic Oil	5.0	+ 10.8	+ 6.7
Piston/Fork	143.4	- 44.8	- 30.4
Torque Link Upper	2.5	+ 6.8	- 0.2
Torque Link Lower	2.7	+ 1.8	- 0.5
TOTALS	292.9	- 39.2	- 42.8

The fabrication costs of the component parts using advanced materials are shown in table XXXII. These costs are, in general, higher for advanced materials, but since most of the parts selected above are lighter, their "effective cost" will change when the "cost of weight" is used to reduce the cost of the parts. The "cost of weight" is the savings which can be realized by the lower weight part when the size of the air vehicle, fuel requirements and the cost factors can be reduced due to the lower weight of a component part. This is the "cascading" effect of weight reduction in the preliminary design stage of an aircraft development program. In the ATS aircraft study this cost was calculated to be $431 per pound. The new costs can be found by calculating changed (Δ) costs with respect to the baseline costs, using this formula:

Total Δ Cost = Δ Unit Production Cost + Δ Cost due to Weight

Where Δ Unit Cost is the change in production cost,
Δ Cost due to Weight = Δ Weight x $431/pound and
$431 per pound is the "Cost of Weight" for the ATS.

Using the weight savings on parts from table XXXVI, for cost savings see table XXXVII. This table shows that while the production unit costs may be higher for advanced materials, the lower weight of these components reduce the cost so that the Organic Advanced Composite parts from Vendor A cost $4,800 less, from Vendor B, $11,550 less and the Advanced Metallic parts cost $14,300 less than the Baseline cost of this group of parts.

TABLE XXXVII
COMPONENT PART UNIT COST COMPARISON
WITH WEIGHT AND GROWTH COST EFFECTS
(on a "nonvolume limited" aircraft)

Weight in pounds/side - Cost in thousands of 1977 Dollars/side - Weight Δ = \$431/lb.

Part Nomenclature	Weight Baseline	Δ Weight/Side		Cost Baseline	Δ Cost/Side			Δ Cost Due to Δ Weight (Δ Wt x .431)		New Δ Cost/Side Including Wt. & Growth Cost Effect (Δ Cost + Δ Cost Due to Weight)		
		Org. Adv'd Comp.	Adv'd Met.		Vendor A Org. Adv'd Comp.	Vendor B Org. Adv'd Comp.	Adv'd Met.	Org. Adv'd Comp.	Adv'd Met.	Vendor A Org. Adv'd Comp.	Vendor B	Adv'd Met.
Strut Cylinder	139.3	-13.8	-18.4	14.3	+ 1.0	-3.59	-1.2	- 5.9	- 7.9	- 4.9	- 9.5	- 9.1
Hydraulic Oil	5.0	+10.8	+ 6.7	0	0	0	0	+ 4.6	+ 2.9	+ 4.6	+ 4.6	+ 2.9
Piston/Fork	143.4	-44.8	-30.4	11.1	+10.9	+6.32	+5.3	-19.3	-13.1	- 8.4	-12.98	- 7.8
Torque Link Upper	2.5	+ 6.8	- 0.2	0.4	+ 0.2	+1.43	0.0	+ 2.9	- 0.1	+ 3.1	+ 4.33	- 0.1
Torque Link Lower	2.7	+ 1.8	- 0.5	0.4	0.0	+1.20	0.0	+ 0.8	- 0.2	+ 0.8	+ 2.0	- 0.2
TOTALS	292.9	-39.2	-42.8	26.2	+12.1	+5.36	+4.1	-16.9	-18.4	- 4.8	-11.55	-14.3

SECTION VI

LIFE CYCLE COSTS

6.1 PHASE I - LIFE CYCLE COSTS

The life cycle costs presented in Phase I were those for the B-1 nose gear which was the baseline for that phase. The Life Cycle Cost for the B-1 nose gear is $24,702,638, based on 240 aircraft and a 10 year time span. This is detailed in the Phase I Report in Appendix A. Since the baseline has been changed for Phase II, the above data is presented for information only.

6.2 PHASE II - LIFE CYCLE COSTS

This section of the program presents the results of the Phase II Design Studies and the Analysis and Evaluation sections in terms of Life Cycle Cost, which is the total cost over the life of the air vehicle. Included are all costs associated with designing, procuring and operating the landing gear for a 10 year period. These costs are divided into five major categories; Development, Production, Support, Fuel Costs and Accident Costs.

The life cycle cost study for the baseline, covered in Section III, described the methodology used to estimate the development, production and support costs. In addition to these direct costs, the change in cost due to weight changes has also been calculated. The basis for this cost is that a revision to the size and cost of the aircraft and to the operating cost is necessary if the weight of the landing gear or nacelle is changed. This cost has been added to table XXXVIII as line items and is a Δ to the cost of the organic advanced composite or the advanced metallic design for the development, production and support costs.

Life Cycle Costs for all five categories are shown in table XXXVIII. The Development cost for the Advanced Metallic design will be $670,500 less, the Organic Advanced Composite design from Vendor A will be $4,648,100 more, and from Vendor B $4,258,100 more than the baseline.

Production costs are $3,258,400 less for the Advanced Metallic design, for the Organic Advanced Composites design from Vendor A, $35,640,400 more and from Vendor B $19,574,600 more than the baseline.

The Support Costs include spares and personnel costs, but since the operational support equipment (OSE) is the same for each design, it was not calculated. The Advanced Metallic design Support Costs are $5,909,200 lower, and the Organic Advanced Composites design from Vendor A are $15,147,300 higher and from Vendor B $14,755,900 higher than the baseline.

TABLE XXXVIII
LIFE CYCLE COSTS BY CATEGORY
(In Thousands of Dollars)

		No Weight Effect			With Weight Effect		
	Baseline	Vendor A Total Composite	Vendor B Total Composite	Titanium	Vendor A Δ Composite	Vendor B Δ Composite	Δ Titanium
DEVELOPMENT COST							
Engr Tooling & Prototype	1,505.4	2,493.4	2,103.4	2,186.2	+ 988.0	+ 598.0	+ 680.8
Wt. Gear Δ					+1,432.8	+ 1,432.8	-1,953.8
Wt. Nacelle & Duct Δ					+2,227.3	+ 2,227.3	+ 602.5
Total					+4,648.1	+ 4,258.1	- 670.5
PRODUCTION COST							
Nonrecurring	590.4	402.2	402.2	425.3	- 188.2	- 188.2	- 165.1
Recurring	40,549.0	52,126.8	36,061.0	46,409.5	+11,577.8	- 4,488.0	+ 5,860.5
Wt. Gear Δ					+ 9,493.4	+ 9,493.4	-12,945.6
Wt. Nacelle & Duct Δ					+14,757.4	+14,757.4	+ 3,991.8
Total					+35,640.4	+19,574.6	- 3,258.4
SUPPORT COST							
Spares	6,150.8	6,589.2	6,197.8	5,936.2	+ 438.4	+ 47.0	- 214.6
Personnel	3,676.8	3,416.8	3,416.8	3,509.0	- 260	- 260	- 167.8
OSE (Not counted - No difference)							
Wt. Gear Δ					+ 5,859.7	+ 5,859.7	- 7,990.5
Wt. Nacelle & Duct Δ					+ 9,109.2	+ 9,109.2	+ 2,463.7
Total					+15,147.3	+14,755.9	- 5,909.2
FUEL COST							
Wt. Gear Δ					+ 972.4	+ 972.4	- 1,326.0
Wt. Nacelle & Duct Δ					+ 1,511.6	+ 1,511.6	+ 408.8
Total					+ 2,484.0	+ 2,484.0	- 917.2
ACCIDENT COST	18,105.0	-0-	-0-	5,974.7	-18,105.0	-18,105.0	-12,130.3
GRAND TOTAL	70,577.4	65,028.4	48,181.2	64,440.9	+39,814.8	+22,967.6	-22,885.6

Fuel costs were not calculated for the baseline aircraft in Section III since, for the purposes of this comparison study, only fuel cost differences between the designs are important. In this section the net difference in fuel consumption due to weight differences between the designs is calculated and presented as a fuel cost. These costs, shown in table XXXVIII are a Δ to both the Advanced Metallic design, \$917,200 less, and to the Organic Advanced Composite design, Vendor A and Vendor B, \$2,484,000 more.

Accident costs are a result of the safety hazzard caused by corrosion related failures as presented in Section III for the Baseline. The assumption has been made that titanium is 67% corrosion resistant compared to steel and that composites are totally corrosion free. These accident costs are presented in table XXXVIII and are a Δ to both Vendor A and Vendor B composite, \$18,105,000 less and to Advanced Metallic \$12,885,600 less than baseline.

The total Life Cycle Cost (LCC) of the Advanced Metallic design is \$22,885,600 less and the Organic Advanced Composite from Vendor A \$39,814,800 more and from Vendor B \$22,967,600 more than the baseline total LCC of \$70,577,400.

This analysis shows that the Advanced Metallic SPF/DB titanium is the most cost effective material system for the ATS airplane. It also shows that the evaluation made in Section V and summarized in table VI cannot fully evaluate the studies since it does not account for the major effect of both the weight of the landing gear and the weight of the added nacelle structure. Table XXXIX presents the same LCC data in a format which shows the magnitude of the weight and growth factors. It shows that these factors reversed the total LCC for both Vendor A and Vendor B, Organic Advanced Composite design.

While both advanced material systems show LCC savings over the baseline, when weight and growth effects are not considered, the larger and heavier Organic Advanced Composite shows a reversal from LCC savings of \$5,550,000 and \$22,400,000 to a \$39,800,000 and \$23,000,000 LCC increase for Vendor A and Vendor B respectively. The LCC savings, over the baseline system, for the Advanced Metallic (Titanium) system increased from \$6,100,000 to \$22,900,000 when weight and growth effects are considered.

The Life Cycle Cost are:

Baseline	= \$ 70,577,400
Organic Advanced Composite	
Vendor A	= \$110,392,200
Vendor B	= \$ 93,545,000
Advanced Metallic - Titanium	= \$ 47,691,800

TABLE XXXIX
TOTAL LIFE CYCLE COSTS
(In Thousands of Dollars)

	Baseline	Vendor A Total Composite	Vendor B Total Composite	Titanium	Vendor A Δ Composite	Vendor B Δ Composite	Δ Titanium
SUMMARY OF TOTALS							
WITHOUT WEIGHT & GROWTH FACTORS							
Development	1,505.4	2,493.4	2,103.4	2,186.2	+ 988.0	+ 598.0	+ 680.8
Production	41,139.4	52,529.0	36,463.2	46,834.8	+ 11,389.6	- 4,676.2	+ 5,695.4
Support	9,827.6	10,006.0	9,614.6	9,445.2	+ 178.4	- 213.0	- 382.4
Accident	18,105.0	-0-	-0-	5,974.7	- 18,105.0	- 18,105.0	- 12,130.3
Subtotal	70,577.4	65,028.4	48,181.2	64,440.9	- 5,549.0	- 22,396.2	- 6,136.5
WEIGHT & GROWTH FACTORS							
Wt. Gear Delta					+ 17,758.3	+ 17,758.3	- 24,215.9
Wt. Nacelle & Duct Delta					+ 27,605.5	+ 27,605.5	+ 7,466.8
Subtotal Wt. Delta					+ 45,363.8	+ 45,363.8	- 16,749.1
GRAND TOTAL Δ					+ 39,814.8	+ 22,967.6	- 22,885.6
GRAND TOTAL	70,577.4	110,392.2	93,545.0	47,691.8			

The Life Cycle Cost analysis presented is specifically for the ATS airplane which is "volume limited," and would not be the same for an aircraft which is not volume limited since the weight and growth factors would be different.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 PHASE I - CONCLUSIONS

The conclusions reached after the Phase I section are listed in the Phase I Report which is presented in Appendix A of this report. The most important conclusion drawn was that the usage of composite material for landing gear components can be increased as design freedom is increased.

7.2 PHASE II - CONCLUSIONS

The design studies, analysis and evaluations made in Phase II of this program resulted in the following conclusions:

1. Where installation requirements will allow, the most compact and simple landing gear will be most efficient, regardless of material used for fabrication.

2. A "leaf spring" configuration landing gear is not a viable concept at this time.

3. Metal Matrix Composites for fabrication of complex, thick, highly loaded landing gear components is not a state-of-the art technology.

4. Reliability of landing gear components is high, but there are differences due to the corrosion resistance of the materials.

5. Development and production costs are the most important costs since they also determine the cost of spares which makeup approximately two-thirds of the support costs.

6. A major increase in the size of an air vehicle to accommodate a larger though lighter landing gear may negate the savings accrued in the landing gear itself.

7. A landing gear for the ATS airplane made from Advanced Metallic SPF/DB titanium will have lower Life Cycle Costs than the baseline steel or the Organic Advanced Composite Gr/Ep landing gear.

8. Landing gear designs using Organic Advanced Composite material are practical and would be cost effective in an installation where the aircraft is not volume limited in the landing gear wheel well area.

9. A Life Cycle Cost analysis trade study must be performed to obtain a true assessment of the cost impact of major changes in the material or configuration of the landing gear.

7.3 RECOMMENDATIONS

Full sized landing gear hardware, using either the Organic Advanced Composite (Gr/EP) material, or Advanced Metallic (SPF/DB titanium) material, should be developed and used on the next new Air Force airplane when trade studies and a Life Cycle Cost Analysis shows that either material is cost effective for the specific installation.

A landing gear development program using titanium, fabricated by superplastic forming and diffusion bonding, should be started so that additional design, analysis, test and cost data can be provided for Life Cycle Cost trade studies to assess the cost effectiveness of new or replacement landing gears.

☆U.S.Government Printing Office: 1978 — 757-080/27